Exploring the New World of Neutrino Physics

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Fermilab Academic Lecture Series

Section III - Spring 2006

Lecture 1 - Beams, decays, and signals of oscillation

What this Course is about

- Concentrate on specific examples of current and future oscillation physics.
- Discuss them in the context of general principles which unify them.
- Occasional “sidebars” for interest.
- Focus on things going on at Fermilab or with lab participation.
- Understand limitations and fundamental systematics.
- Discuss future neutrino sources needed for precision work.

What this Course is NOT about

- Not a general review of all neutrino physics, or even all oscillations,
- Not a detailed quantitative comparison of various proposed or running experiments
- No discussion of lots of interesting areas
  - Solar neutrinos
  - Purely atmospheric experiments (except in passing)
  - Double beta-decay
  - Astrophysical neutrinos

Basics of Neutrino Oscillation Experiments

As in all neutrino experiments, basically counting experiments.

(1) Secondary particle creation

e.g. $$pN \rightarrow n\pi^{\pm} + X$$ Model Uncertainties

(2) Decay and projection of secondaries

e.g. $$\pi^{+} \rightarrow \mu^{+}\nu_{\mu}$$ Understood.

(3) Oscillation or new physics

$$\nu_{\alpha} \rightarrow \nu_{\beta}$$ To be measured

(4) Interactions in detector

Charged Current (CC) $$\nu_{\alpha}N \rightarrow \ell_{\alpha}X$$

Neutral Current (NC) $$\nu_{\alpha}N \rightarrow \nu_{\alpha}X$$

Model Uncertainties

(5) Measurement in detector

Usual problems

Refinements on the Basic Idea

May sub-divide counting by categories

- Type of lepton in CC, μ, e, τ

- Kinematic variables:

e.g $E_{\nu,}$, $y = E_{hadrons}/E_\nu$

Basic measurement is

$$N = \varphi_\nu(E_\nu)\sigma_\nu(E_\nu)$$

flux   cross-section of interest

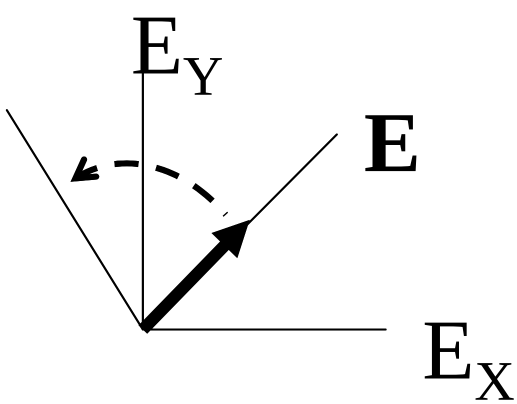
Must deconvolute using inference, simulation, previous data, and ratios

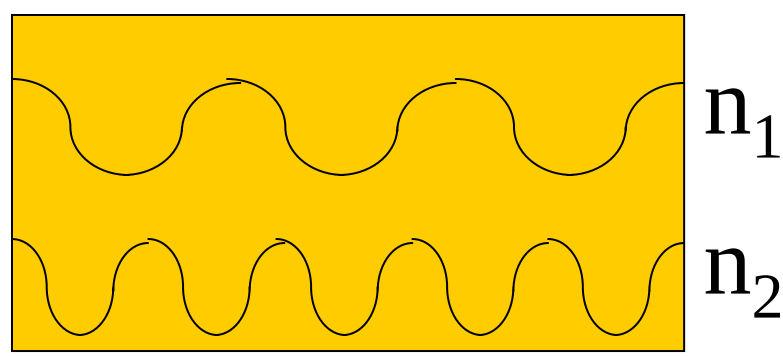
Sidebar-Neutrino Oscillations - Optical Analogy

Birefringent crystal - different index of refraction (light speed) for different polarizations

Polarization rotates because of differential phase advance

$$R = \frac{e^{ik_1 x}}{e^{ik_2 x}}$$





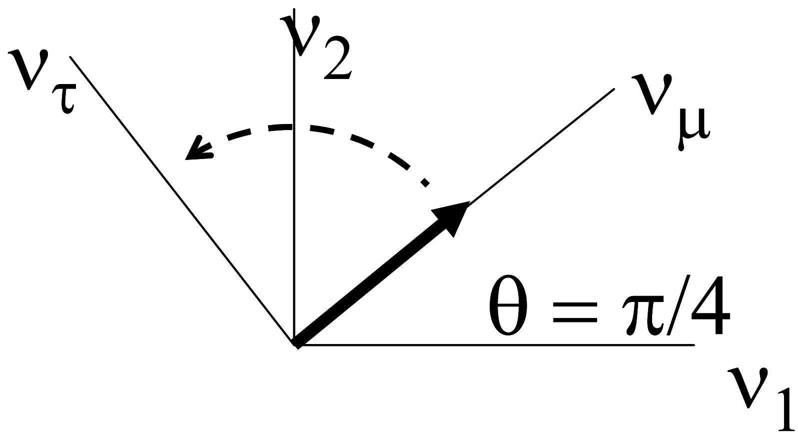
For neutrinos

$$k = \frac{\omega}{c} n = \frac{\omega}{c} \beta \qquad m\gamma = E_\nu$$

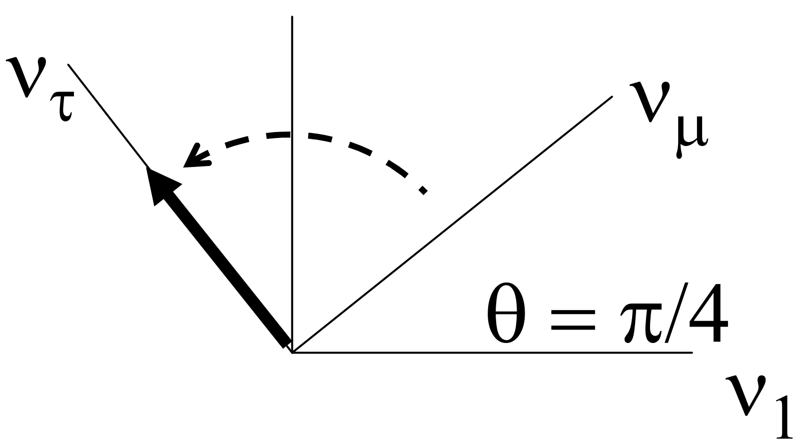
giving

$$R = e^{i\Delta k\, x} = e^{i \frac{m_1^2 - m_2^2}{2E} x}$$

Oscillation as "Flavor Polarization" Rotation



$$L = \frac{2\pi E}{\Delta m^2} = \frac{\pi}{\Delta k}$$



In general case, rotation isn't complete

$$P(\nu_\mu^2) = 1 - \sin^2(2\theta)\sin^2\left(\frac{\Delta k\, x}{2}\right)$$

Categorize experiments as appearance or disappearance

Disappearance - look for a loss of ν flux as a function of spectrum.

Typical $\nu_\mu \rightarrow \nu_x$, where x = e, τ does not leave typical CC muon in the detector.

Flux, spectral knowledge important systematics.

Examples: MINOS, reactor $\bar{\nu}_e$ experiments

Appearance - look for the presence of types of ν's that shouldn't be there.

Here we are finding the ν_x end product of oscillation directly.

Backgrounds now a major systematic!

Examples: NOvA, CNGS, MiniBoone

Two detectors improves control of oscillation measurements

We need to measure P_{osc}, the survival or appearance probability, but what we see is

$$N_{obs}^{far} = (\varphi_\nu \sigma_\nu)_{far}^{true} P_{osc}$$

With the extra measurement at a near detector we can form

$$(\varphi_\nu \sigma_\nu)_{far}^{true} = (\varphi_\nu \sigma_\nu)_{near}^{meas} \frac{(\varphi_\nu)_{far}^{MC}}{(\varphi_\nu)_{near}^{MC}}$$

Our measurement at the near

Well-controlled
systematics on this ratio

2-ν Oscillations in a 3-ν World

General "Euler Rotation" Formalism

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$U = U_{23} U_{13} U_{12}$$

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & s_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

gives

$$P_{\nu_\mu \to \nu_\tau} \propto 4\,(U_{\mu 1} U_{\tau 1} U_{\mu 3} U_{\tau 3} + U_{\mu 2} U_{\tau 2} U_{\mu 3} U_{\tau 3})$$

and

$$P_{\nu_\mu \to \nu_\tau} = \cos^4\theta_{13} \sin^2 2\theta_{23} \sin^2(\Delta_{13})$$

$(\cong 1)$

Ignoring solar oscillations,
Familiar 2-generation formula

Note

$$\Delta_{13} = 1.27 \Delta m_{13}^2 L / E_\nu$$

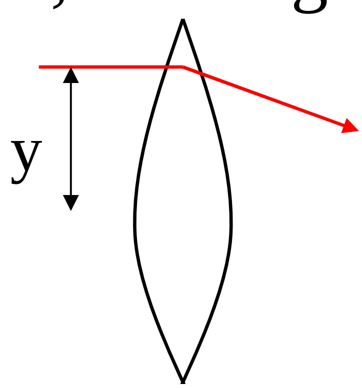
Beam Transport and Secondary Focusing

- Every conventional neutrino experiment starts by focusing a proton beam on a target
- Beamline elements are bending magnets (dipoles) and lenses (quadrupoles and sextapoles)
- There are a variety of ways to focus the secondary particles created in the target, which make neutrinos.
  - Horn focusing
  - Quad focusing
- Will discuss the target physics separately

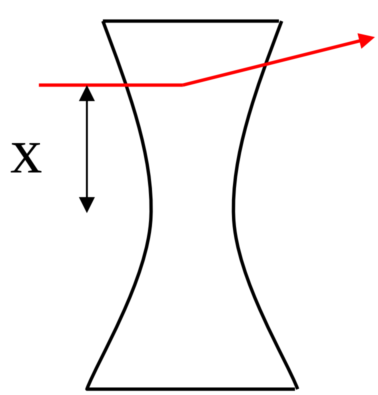
Primary Focusing - Magnetic Quadrupole Lenses

As with all magnets $$P_T = \int B\,dl$$

In a quadrupole magnet, field strength increaseslinearly with distance from axis, forming a lens.



Maxwell’s equations insist that focussing in x must be defocusing in y. (Field direction)



Magnetic Field in a Quadrupole Magnet

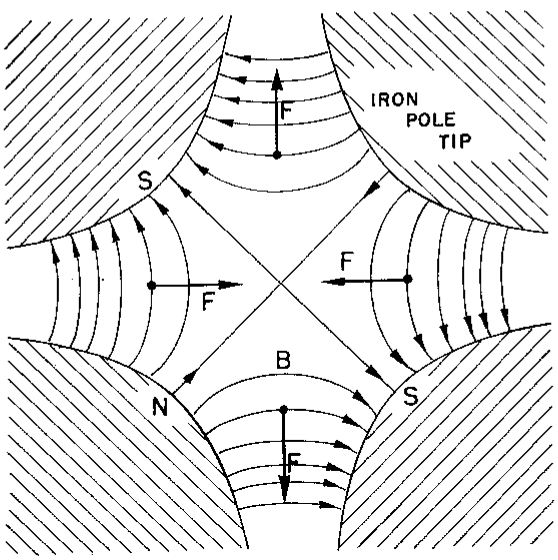


Fig. 29–15. A horizontal focusing quadrupole lens.

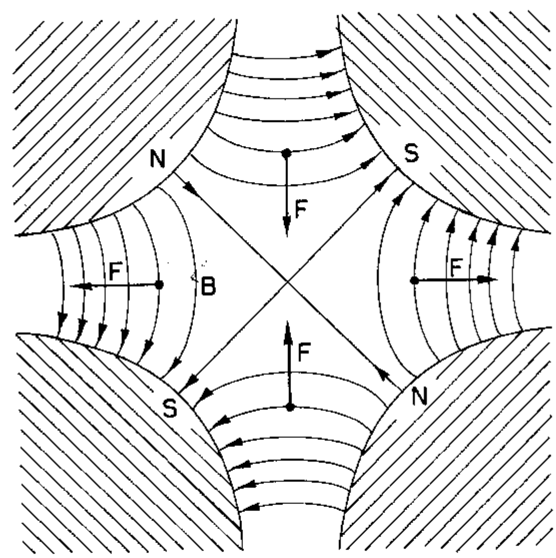


Fig. 29–16. A vertical focusing quadrupole lens.

29–6

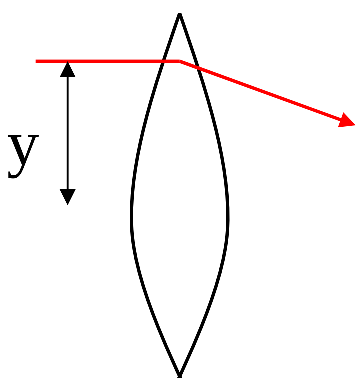
Unlike an optical lens, only focuses one plane.
If the magnet is rotated, it couples motion in the two planes.
There is an analytic formalism to understand this.

Picture from Feynman Lectures on Physics

Transfer Matrix Formalism

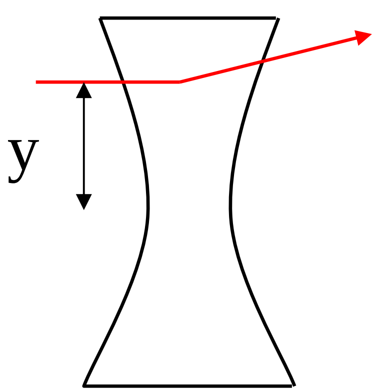
$$\begin{pmatrix} y \\ y' \end{pmatrix} = \begin{pmatrix} position \\ angle \end{pmatrix}$$

focusing from minus



$$\begin{pmatrix} 1 & 0 \\ -1/f & 1 \end{pmatrix} \begin{pmatrix} y \\ 0 \end{pmatrix} = \begin{pmatrix} y \\ -y/f \end{pmatrix}$$

f = focal length



$$\begin{pmatrix} 1 & 0 \\ 1/f & 1 \end{pmatrix} \begin{pmatrix} y \\ 0 \end{pmatrix} = \begin{pmatrix} y \\ y/f \end{pmatrix}$$

defocusing

"FODO" Cell to focus both planes

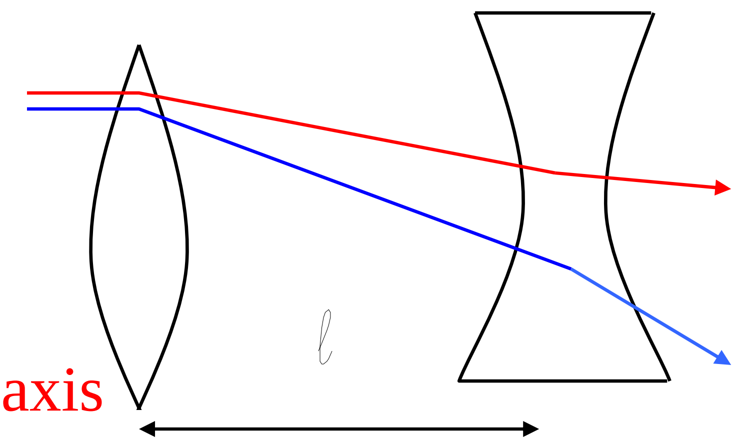
"DO" "drift" "FO"

$$\begin{pmatrix} 1 & 0 \\ 1/f & 1 \end{pmatrix}\begin{pmatrix} 1 & \ell \\ 0 & 1 \end{pmatrix}\begin{pmatrix} 1 & 0 \\ -1/f & 1 \end{pmatrix}\begin{pmatrix} y \\ 0 \end{pmatrix}$$

$$= \begin{pmatrix} y - \ell y/f \\ -\ell y/f^2 \end{pmatrix}$$

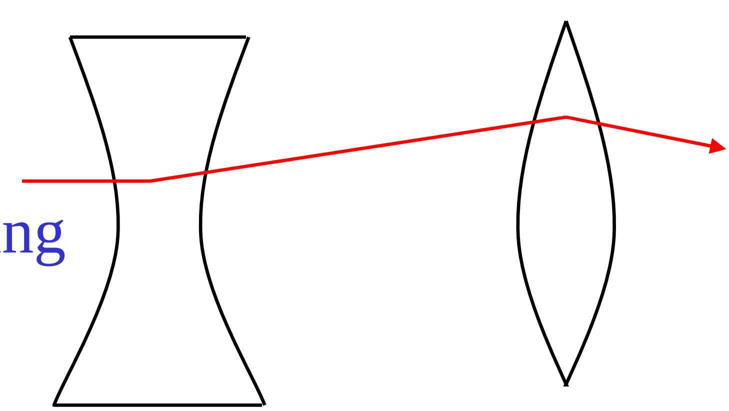
focusing if ℓ < f,

goes like distance from axis

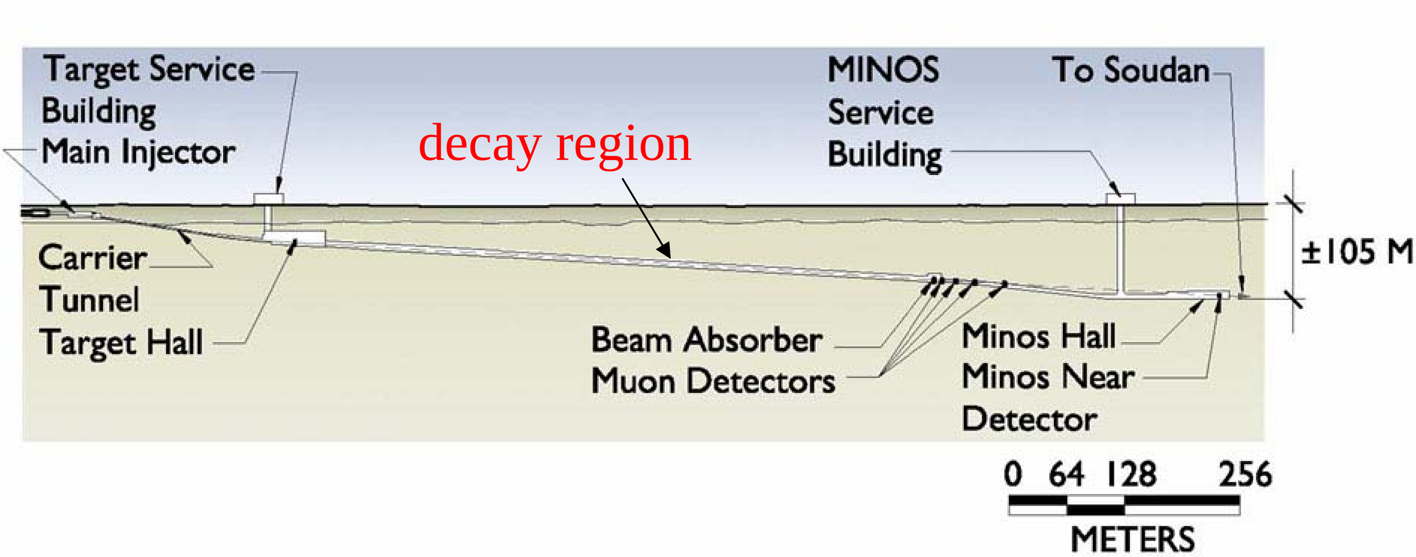


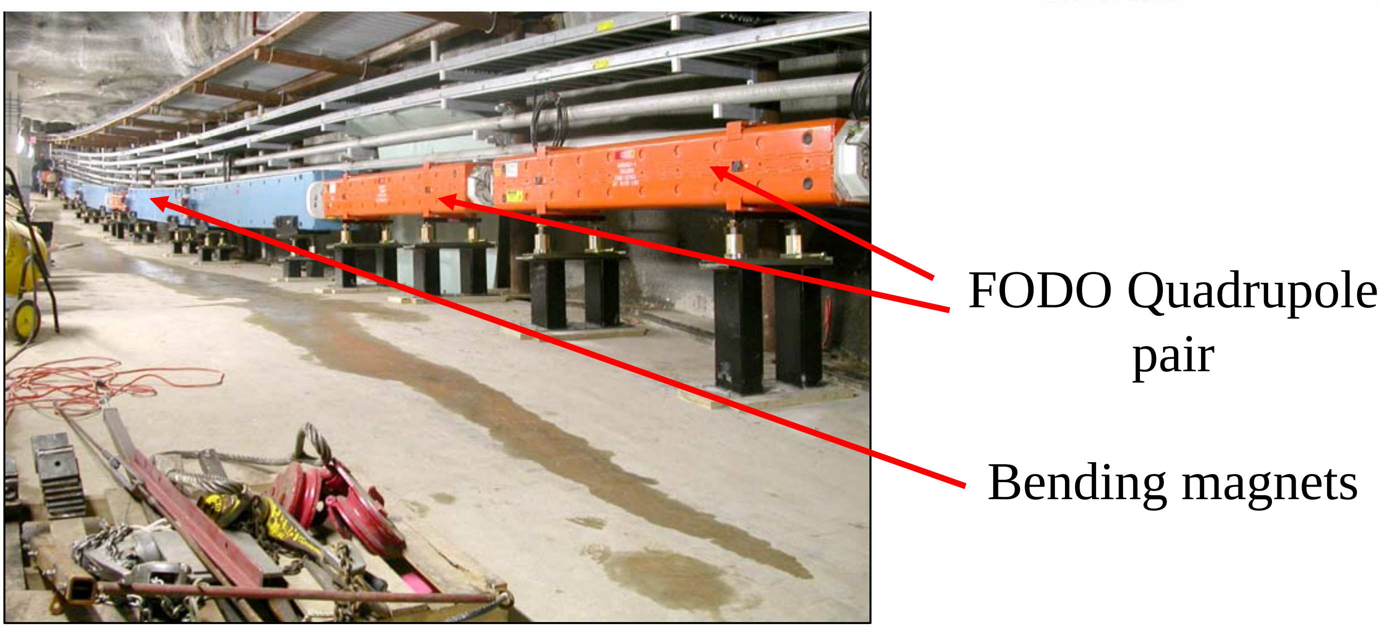
$$\begin{pmatrix} 1 & 0 \\ -1/f & 1 \end{pmatrix}\begin{pmatrix} 1 & \ell \\ 0 & 1 \end{pmatrix}\begin{pmatrix} 1 & 0 \\ 1/f & 1 \end{pmatrix}$$

Other plane also focussing



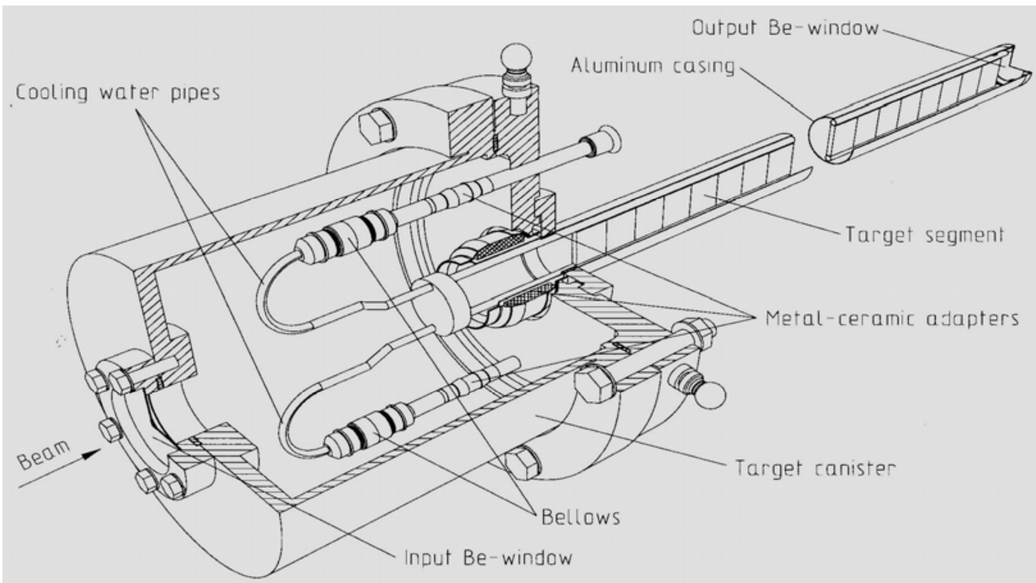
Real Elements of NuMI Beamline





NuMI Pretarget final transport

NuMI Target - where the decaying particles start



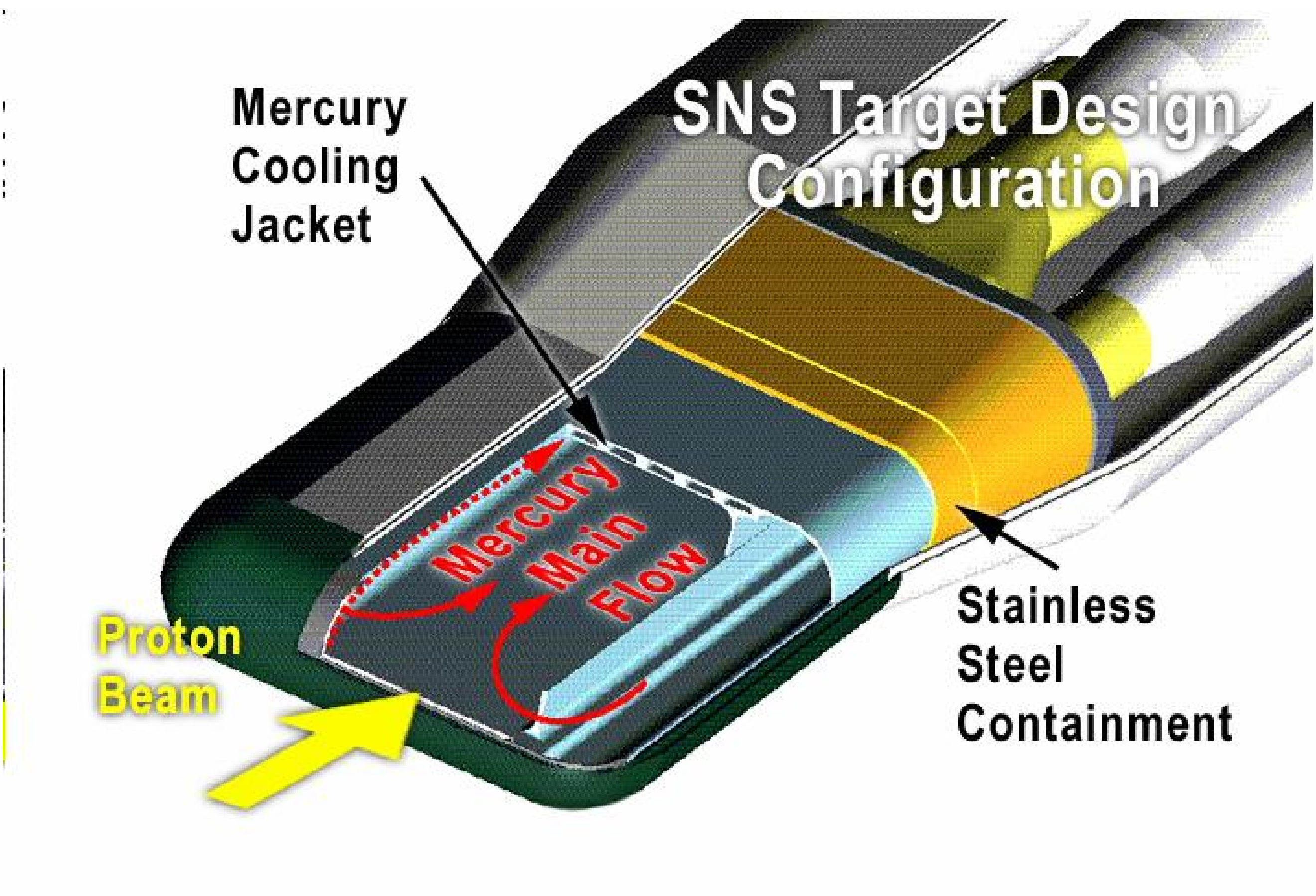
60 cm graphite fins - water cooled
Be windows at either end
Absorbs 40 KW of power at design intensities.
Careful modeling because distribution of particles coming out affects ν flux

Sidebar- advanced targeting

At very high beam powers, targeting becomes more difficult.

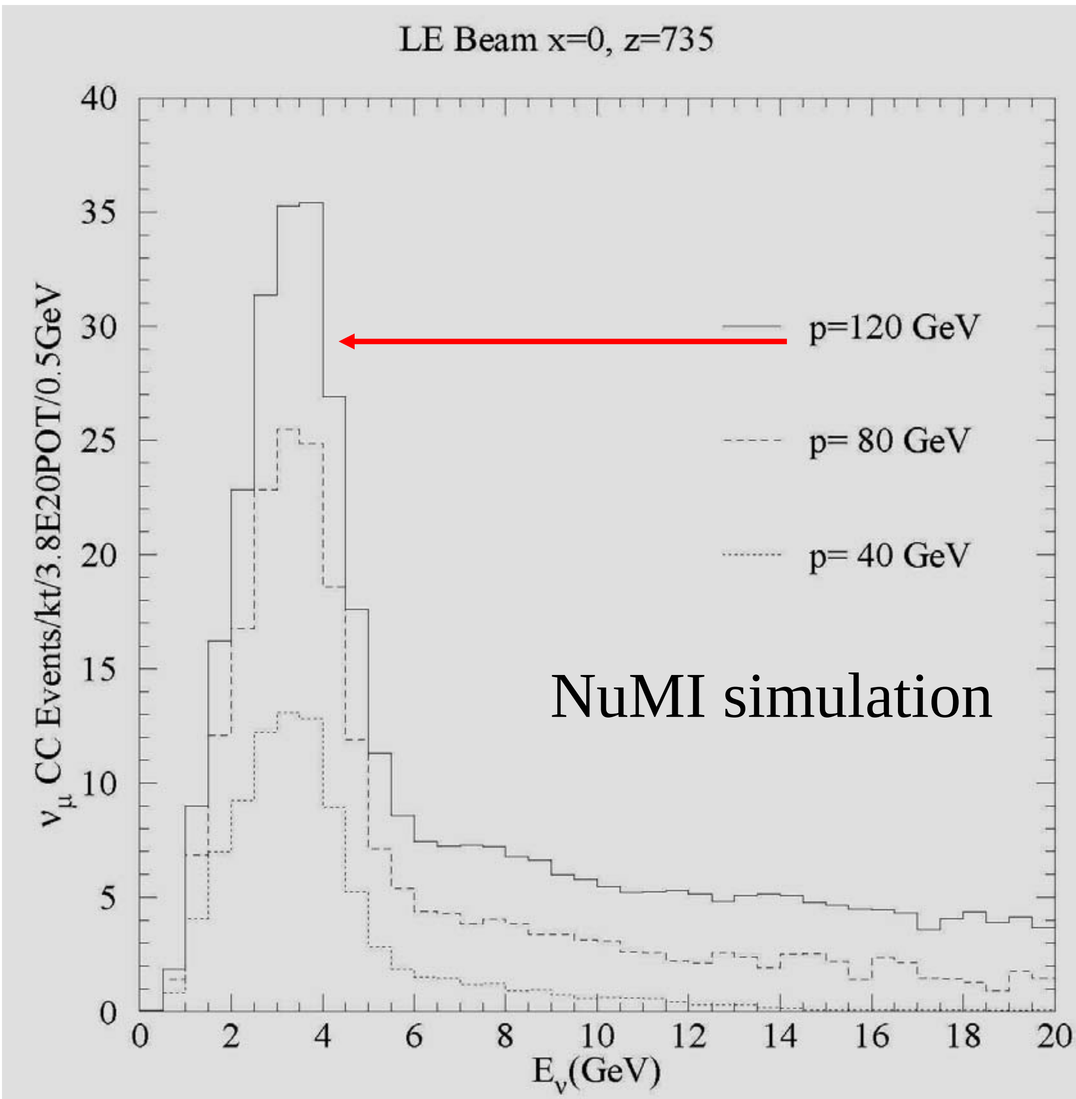
Radiation, heat transfer, shock issues.

SNS flowing liquid mercury target absorbs 2 MW!



Neutrino intensity depends on beam power

Counter-intuitive because fewer incident particles!



As primary beam energy increases, more low x particles are brought within the focussing zone

Secondary Particle Production

π and K production in the target are the ultimate source of neutrino flux

Knowledge and understanding of this is an important systematic for oscillation experiments.

Two types of modeling (using experimental data as input):

-Hadronic cascade Monte Carlos

FLUKA, MARS, GEANT

Tend to be "black boxes"

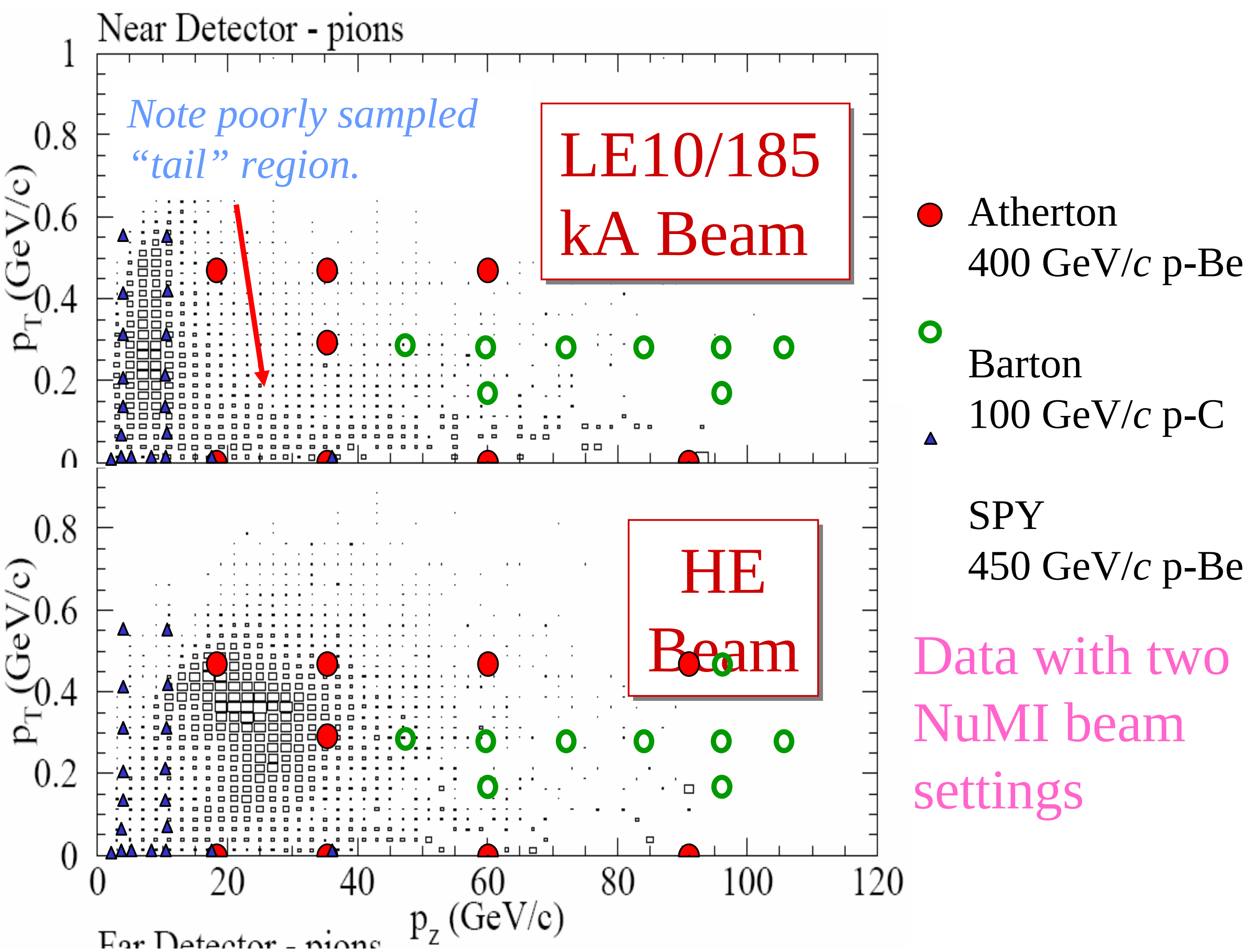
Hard to factorize errors

Parametrized Simulations

Example for these lectures: BMPT

Provide the experimenter with functions, errors

Experimental data compared to NuMI data range



Notes: in parametrizations, data may use scaling variables

$$x_F \equiv 2p_L^* / \sqrt{s}$$

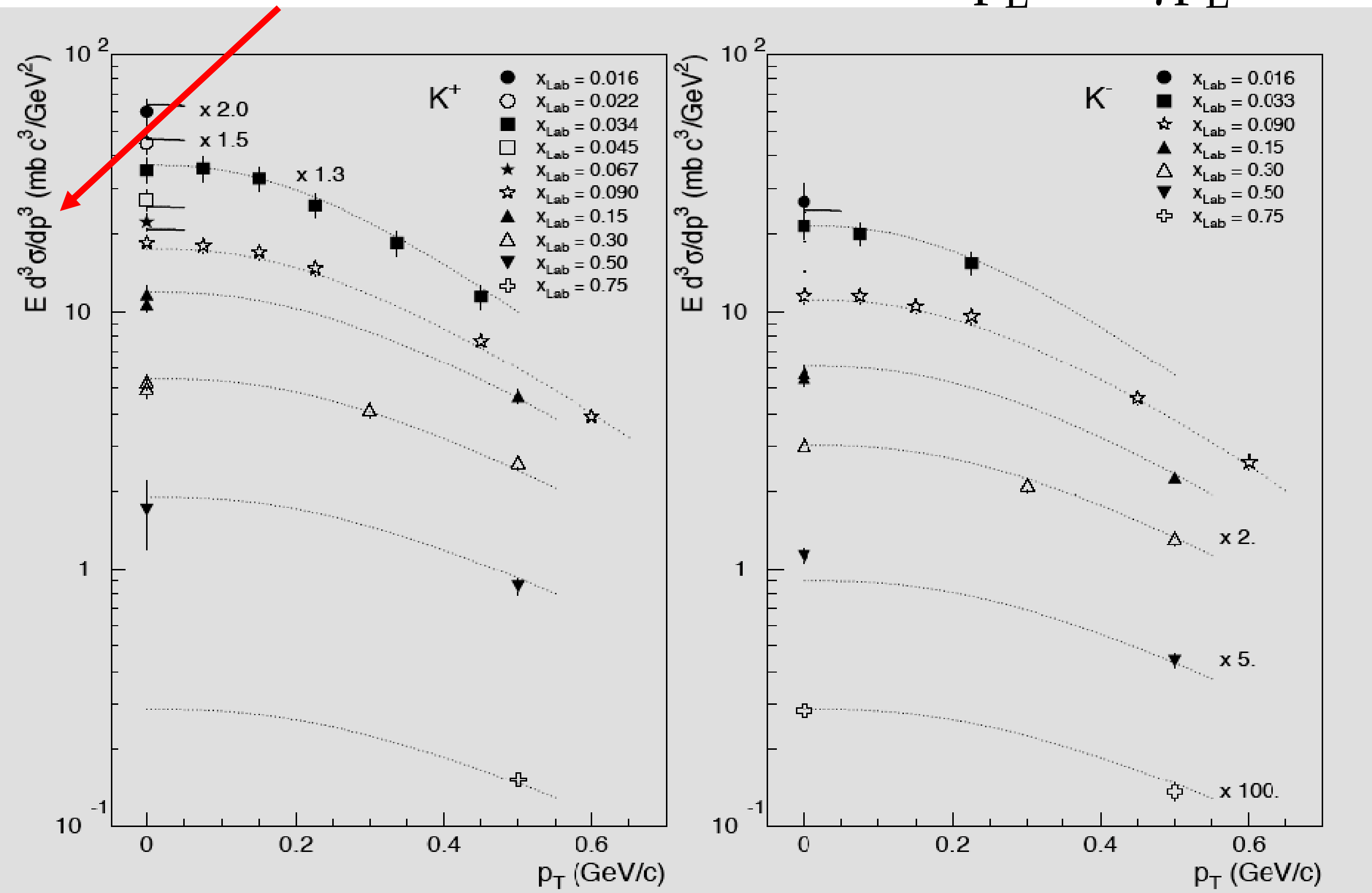
$$x_R \equiv E^* / E^*_{\max}$$

These two very similar, especially for π's

$$x_{lab} \equiv p_{lab} / p_{incident}$$

Example of BMPT parametrization - K's

Invariant cross-section under $p_L \longrightarrow \gamma p_L$



BMPT parametrization

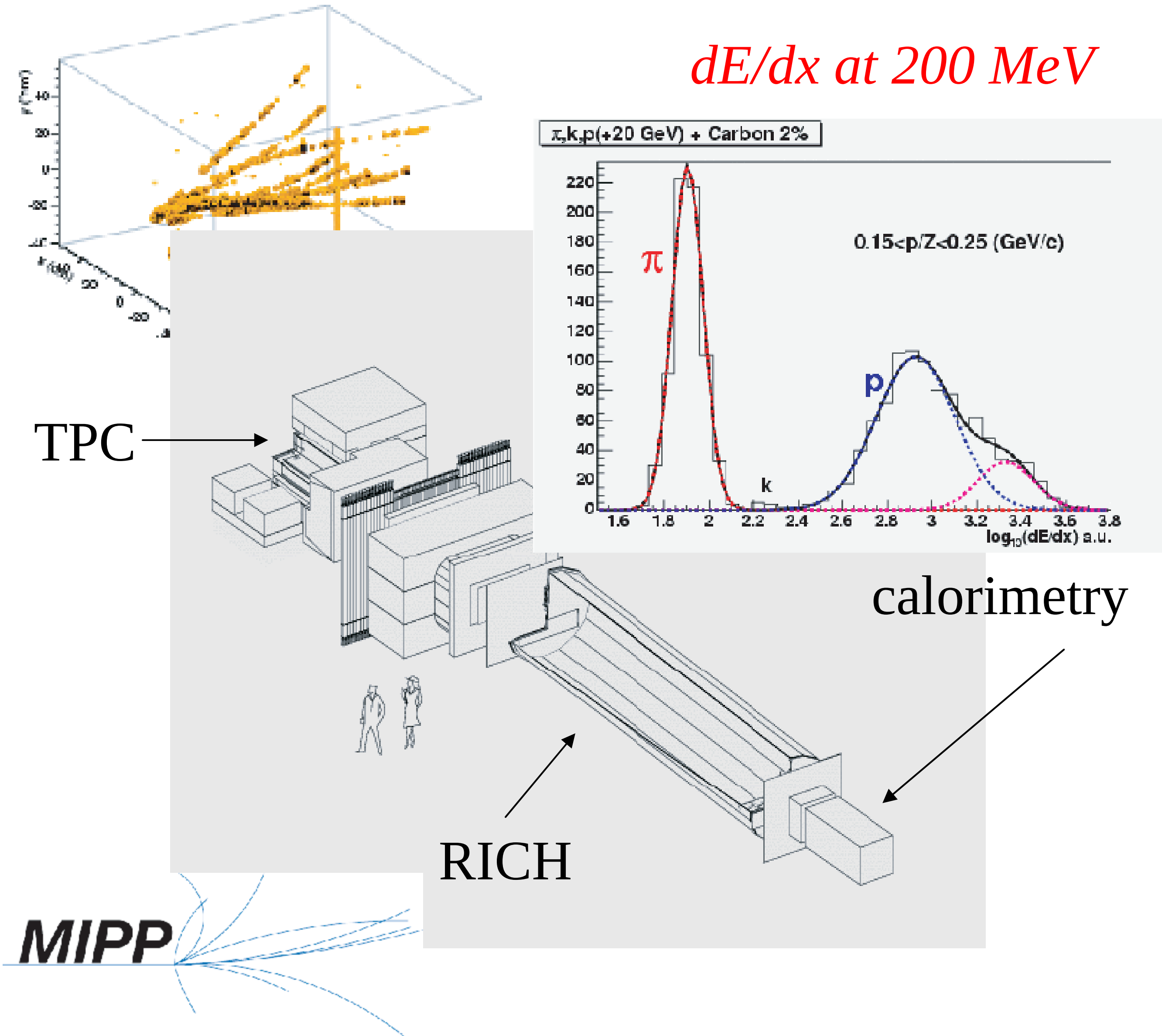
$$E\frac{d^3\sigma}{d^3p} = A(1-x_R)^{\alpha} x_R^{-\beta} G(x_R, p_T) e^{-a(x_R)p_T}$$

Notes: Limited p_T !

Cutoff at high x

Enhancement at low x

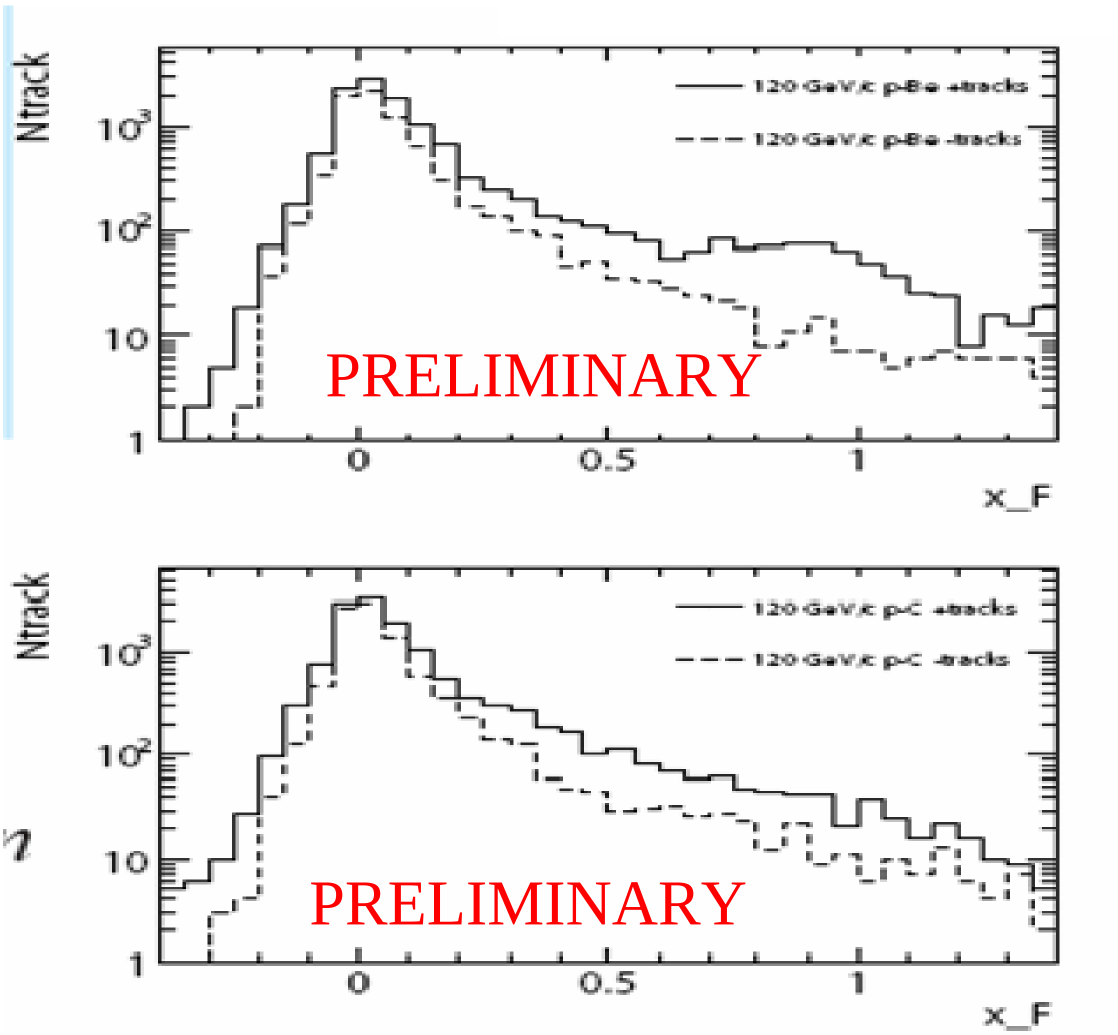
Example of experimental program- MIPP experiment at Fermilab



Study p,K + A interactions from 5-85 GeV
Study p + A interactions at 120 GeV
Measurements on H, Be, C, various metals

Typical MIPP Preliminary Data

MIPP



Inclusive x_F distributions for Be (top) and C (bottom) targets

Working through target list including NuMI target

Coutesy Messier, NOVE-06

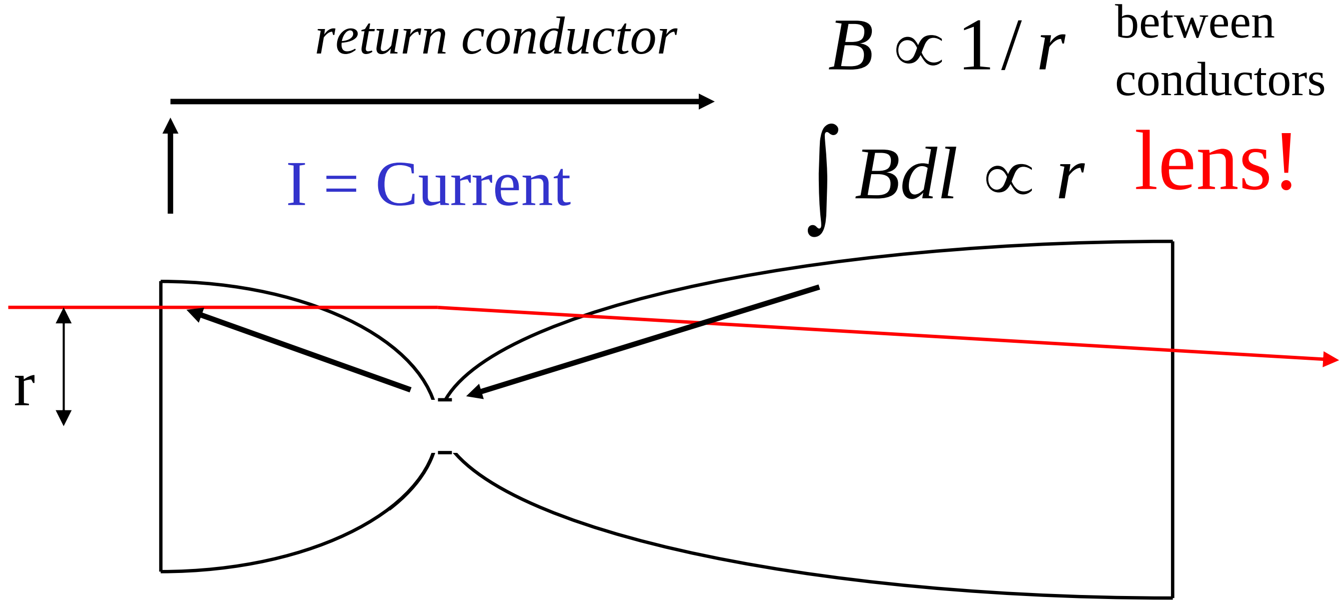
Example of Secondary Focusing: Parabolic Horn

Old technology - form pulsed sheets of current in a cylindrical geometry.

$$L \propto r^2$$

$$B \propto 1/r$$ between conductors

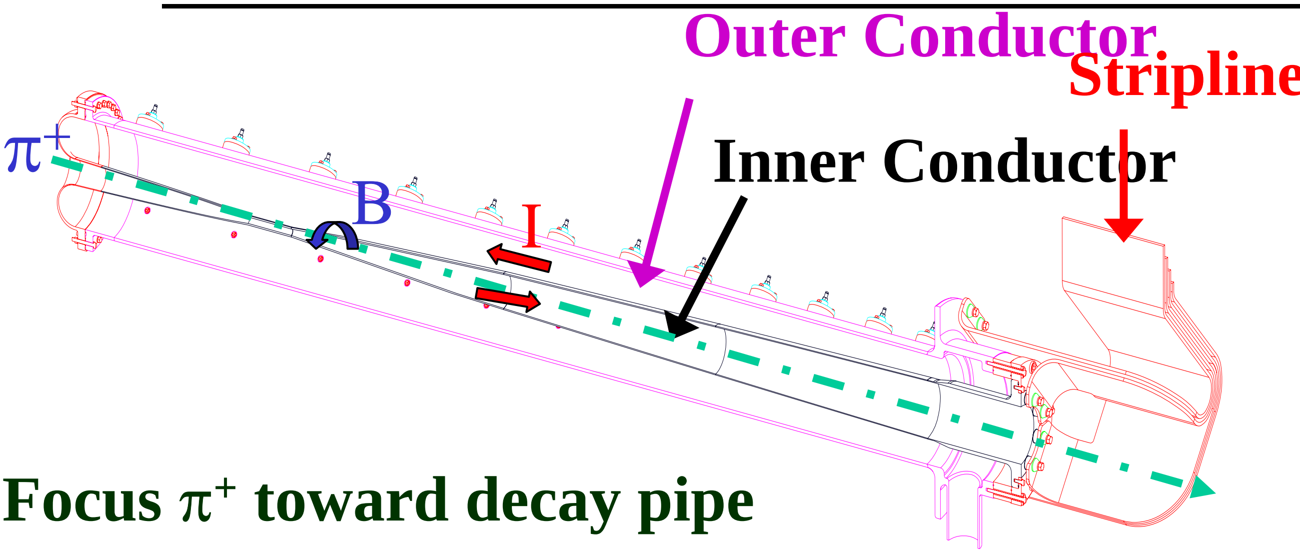
$$\int B dl \propto r$$ lens!



Many variations on this shape have been made, with different momentum acceptances

HIGH CURRENTS - e.g. NuMI horn uses 180 kA for ~2 mS.

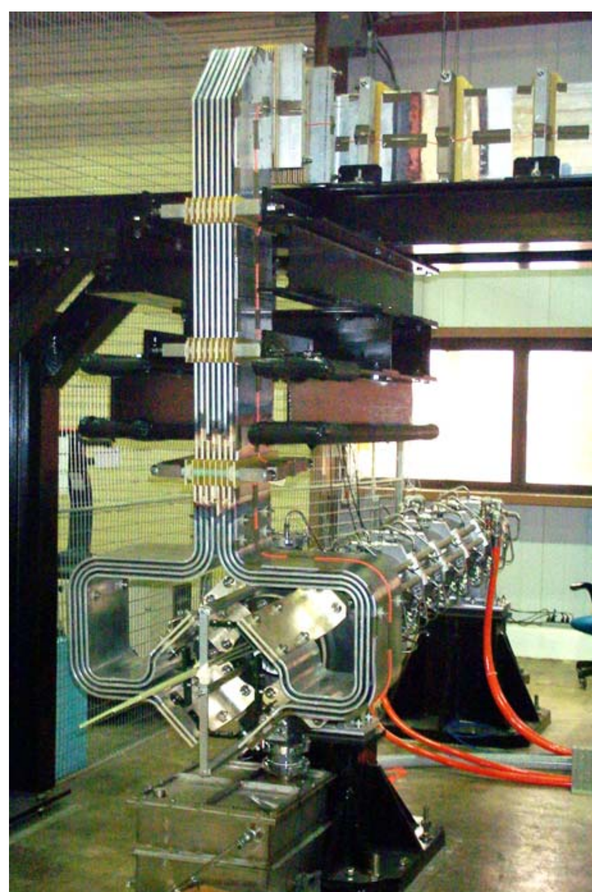
NuMI horn under construction



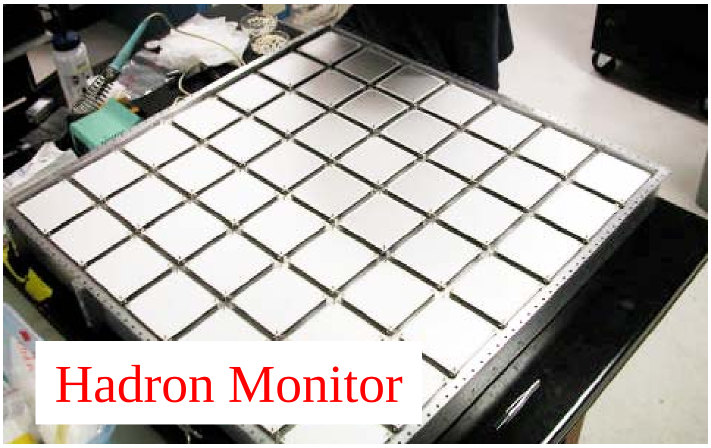
Focus π^+ toward decay pipe

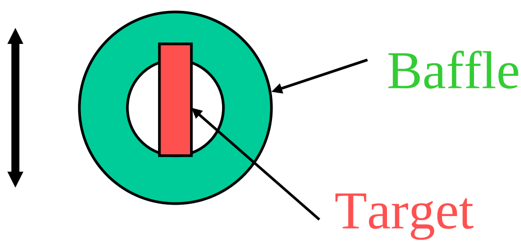
Horn 2 inner conductors

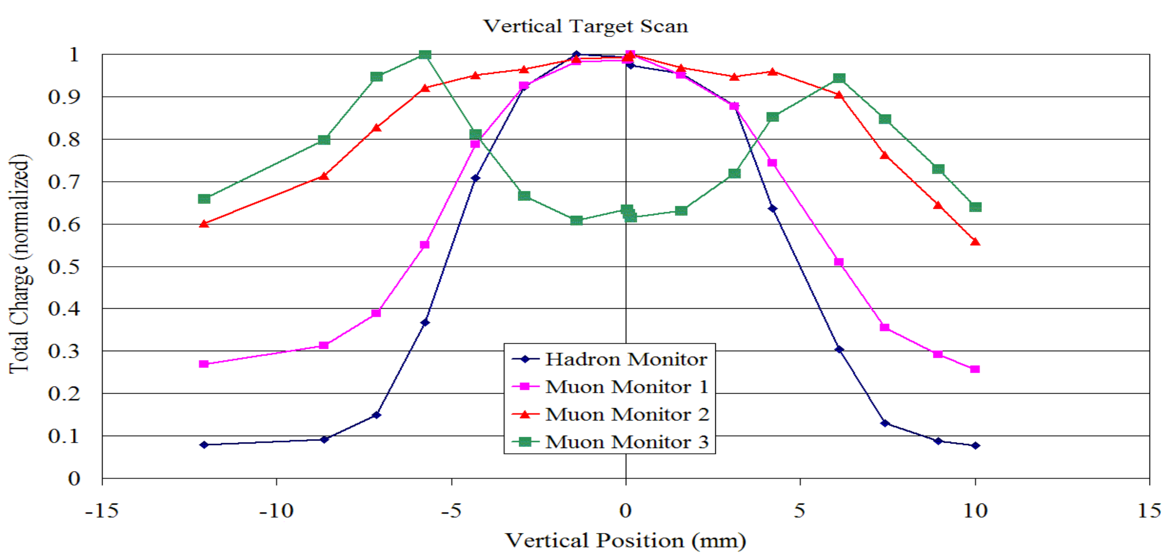
Prototype horn 1 in test stand



Secondary Beam Monitoring







Scan of beam across target shows edges, increased production in outer baffle - real detail!

Neutrinos from π, K Decay - Spectrum

Two-body decay $\pi \rightarrow \mu\nu$ of CM energy E*

Lorenz Transformation of P_L, E

$$M = \gamma(1+\beta\cos\theta^*)$$
$$M\cos\theta = \gamma(\cos\theta^* + \beta)$$

using
$$M \equiv E_{lab} / E^*$$

$$M = \frac{1}{\gamma(1-\beta\cos\theta)}$$
$$\cong \frac{1}{\gamma(1-\cos\theta)} \cong \frac{2\gamma}{1+\gamma^2\theta^2}$$

Spectrum depends on angle

Sharper for increased π energy

Neutrinos from π, K Decay - Flux

Lorenz transform P_T this time

$$E\sin\theta = E^* \sin\theta^*$$

$$M\sin\theta = \sin\theta^*$$

for small angles

$$\sin\theta \cong \theta \Rightarrow \quad M\theta = \theta^*$$

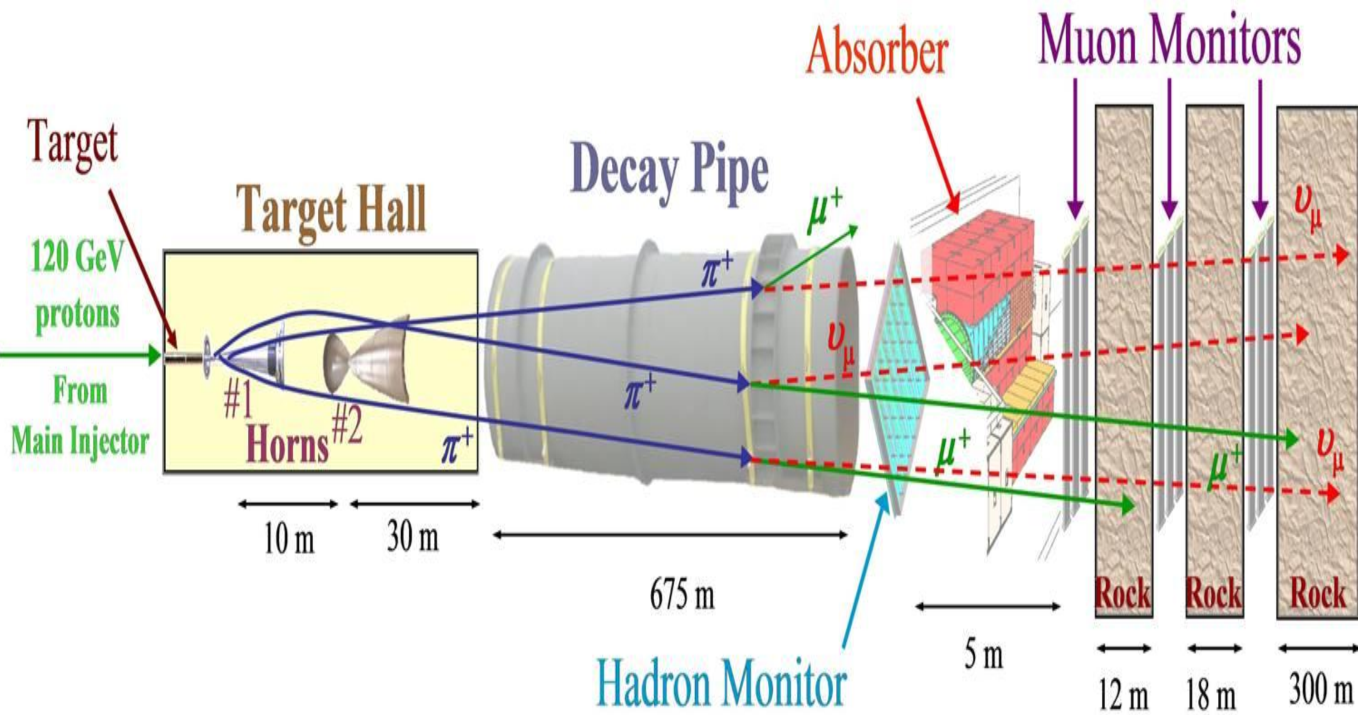
$$\Rightarrow \quad \frac{d\theta^*}{d\theta} = M$$

*actually, this is valid for all values of θ**

giving flux compression factor

$$\boxed{\frac{d\Omega^*}{d\Omega} = \frac{\sin\theta^* d\theta^*}{\sin\theta\, d\theta} = M^2 = \frac{4\gamma^2}{(1+\gamma^2\theta^2)^2}}$$

NuMI Beamline Layout



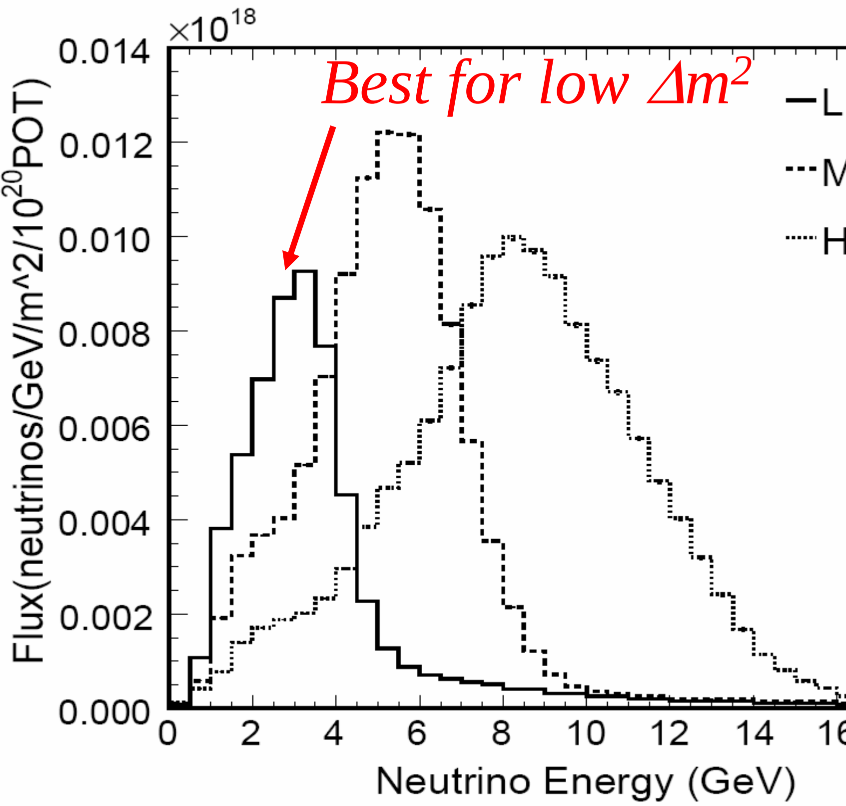
120 GeV primary Main Injector beam

Target readily movable in beam direction

2-horn beam adjusts for variable energy ranges

675 meter decay pipe for π decay

Beam Energy Variability

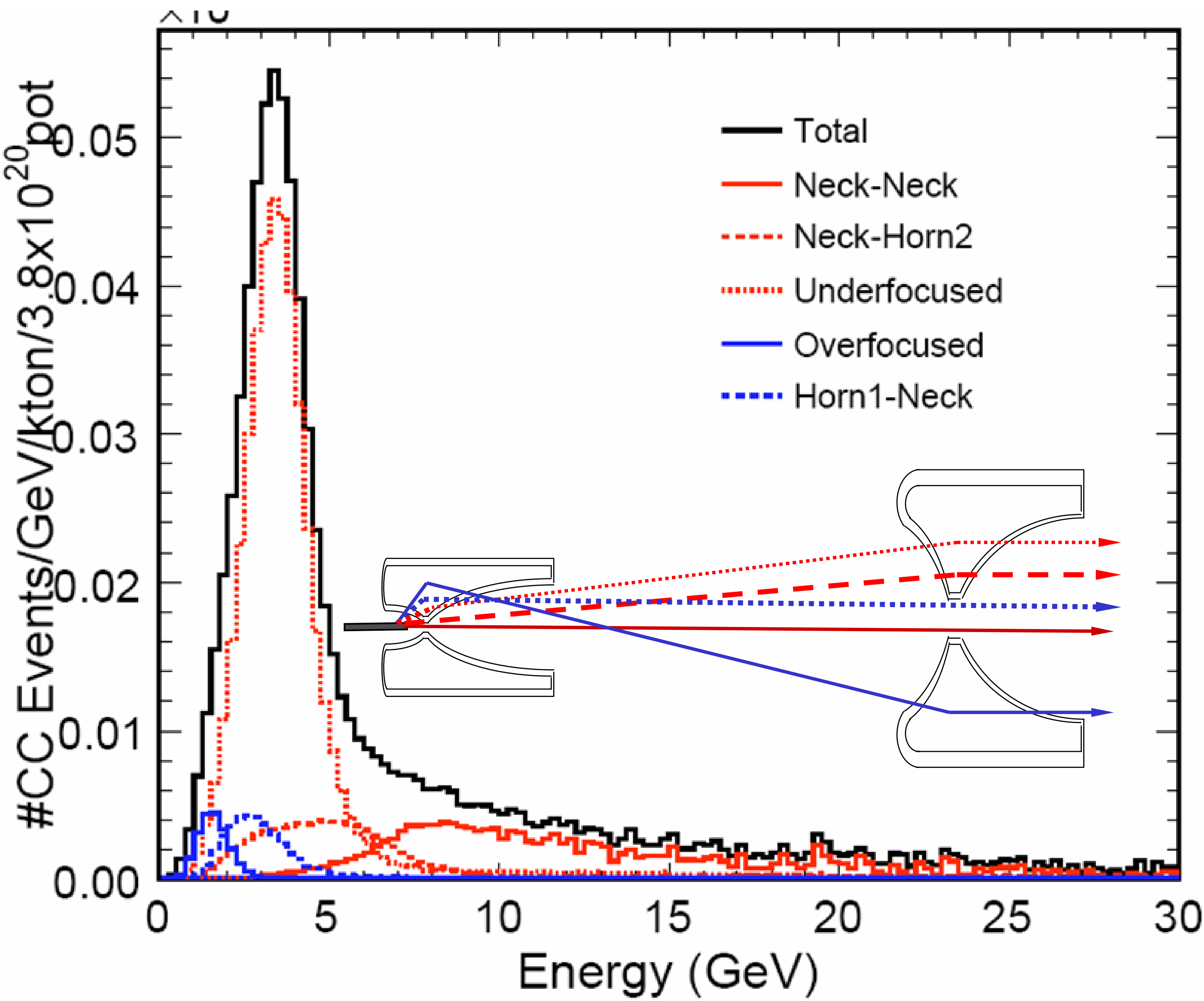


Example spectra from varying horn positions (same effect from moving target)

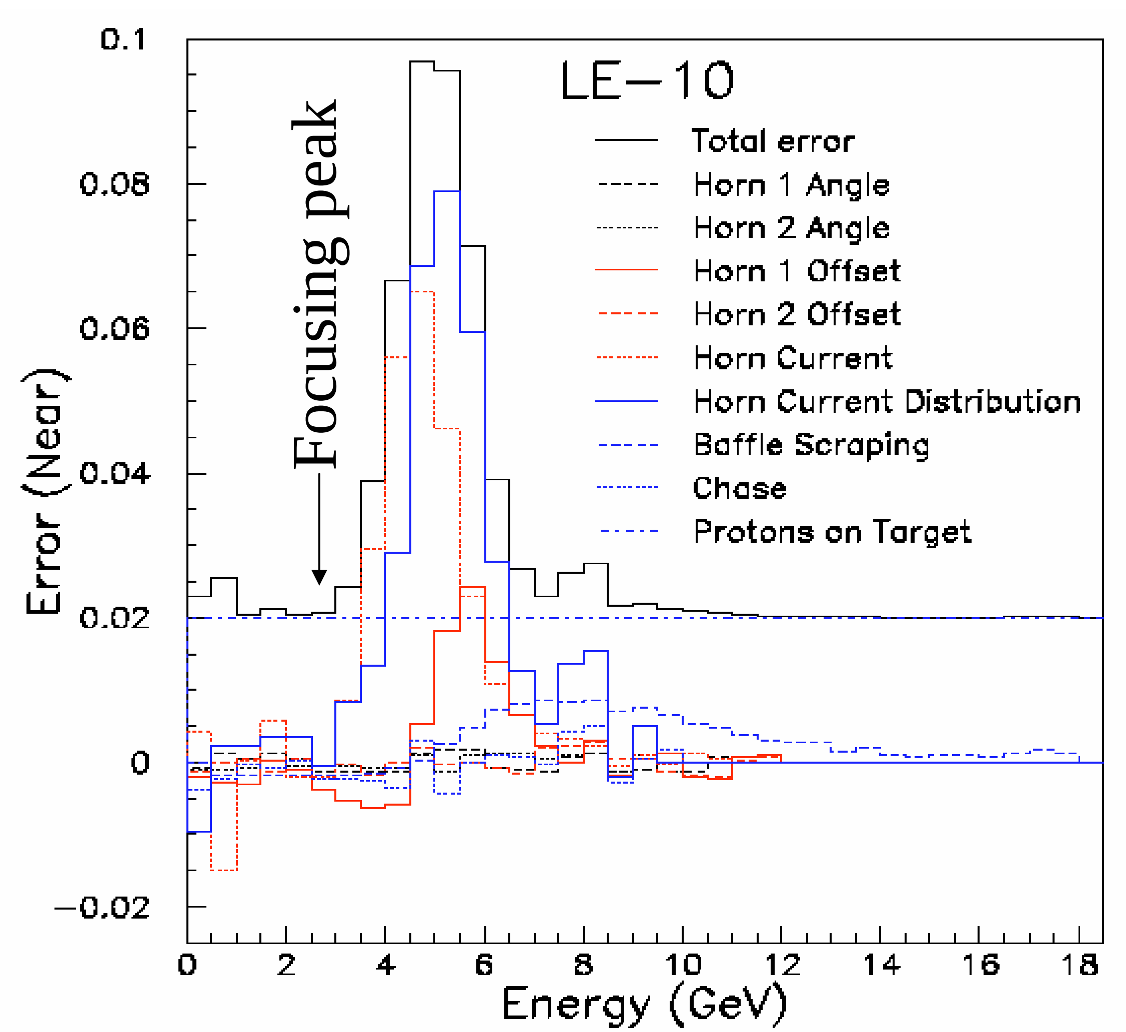
ν_μ CC Events in MINOS 5kt detector (2.5 x 10^{20} POT/yr)

Low	~ 1600/yr
Medium	~ 4300/yr
High	~ 9250/yr

Neutrino Beam 101 (from Sacha Kopp)



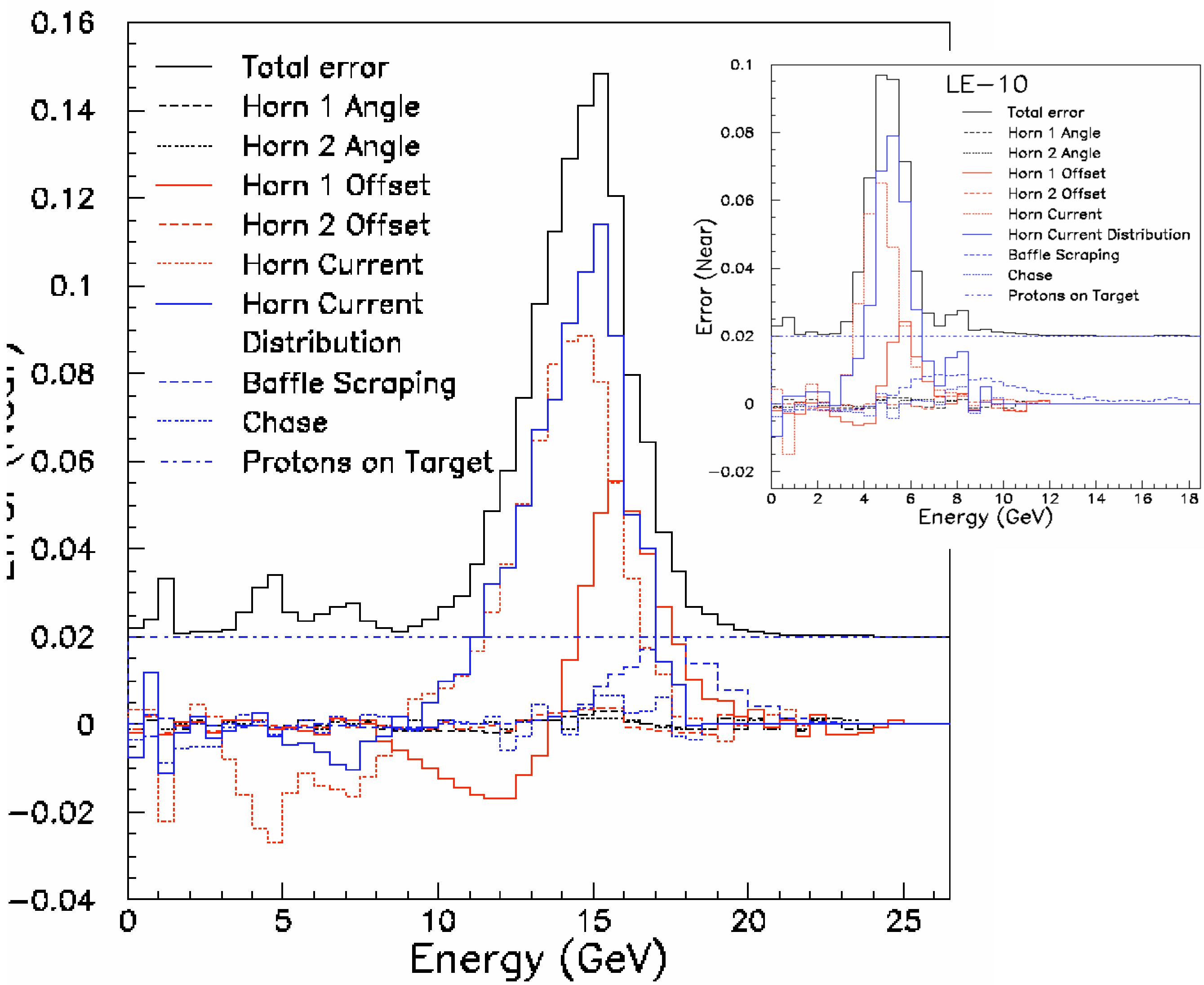
Beamline Flux Fractional Uncertainties in NuMI Beam



Kopp, et. al

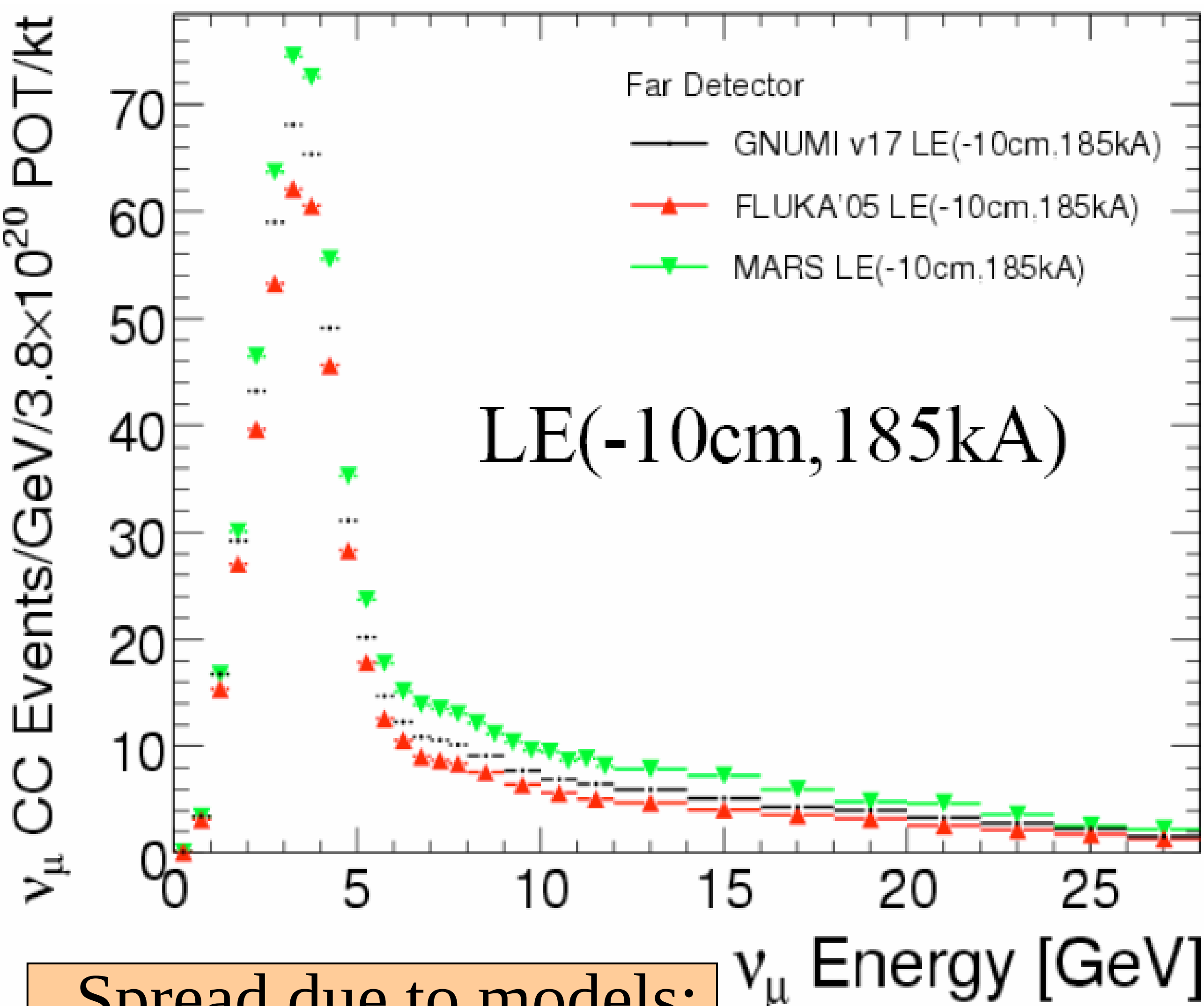
Does not include errors from hadron production model

Study typical uncertainties with beam energy evolution



NuMI high energy beam at near location (inset repeats the low energy plot)

Spread of a neutrino spectrum due to parent hadron uncertainties

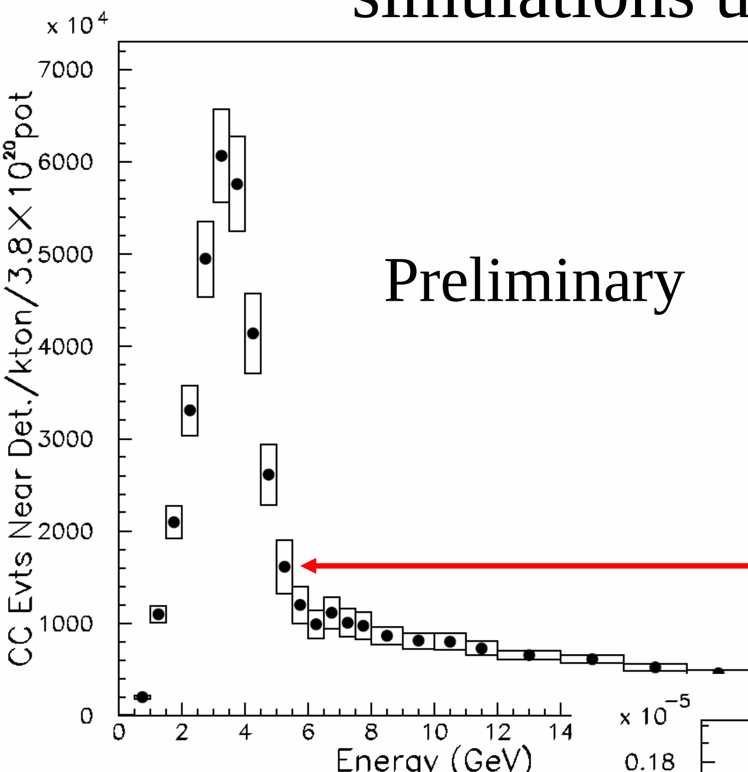


Spread due to models:
8% (peak)
15% (tail)

Kopp, et. al.

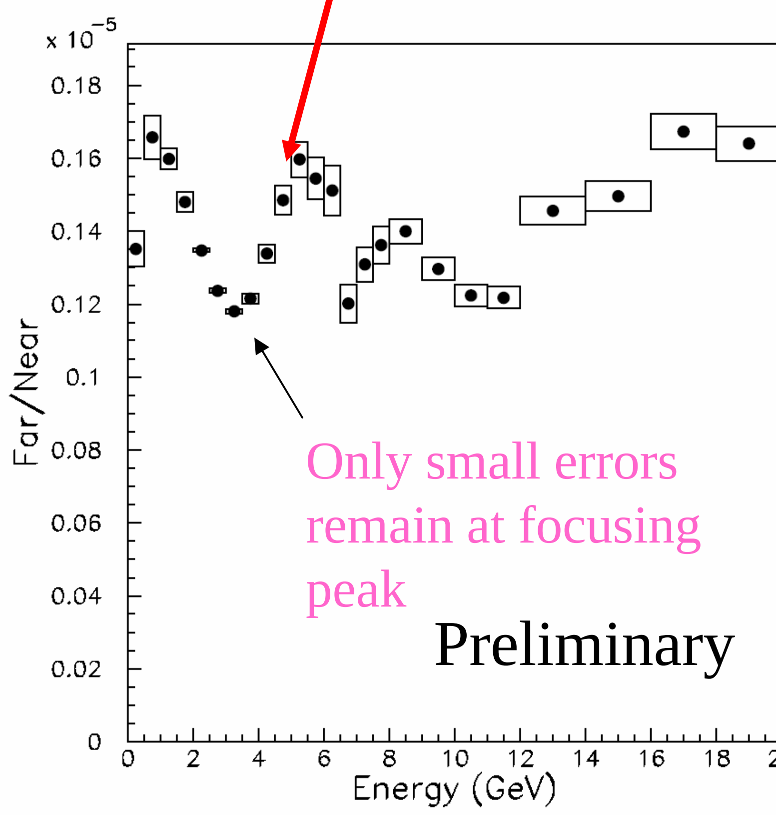
Two detectors to reduce uncertainty

Examples from MINOS simulations using FLUKA



Hadron production uncertainty dominates this plot

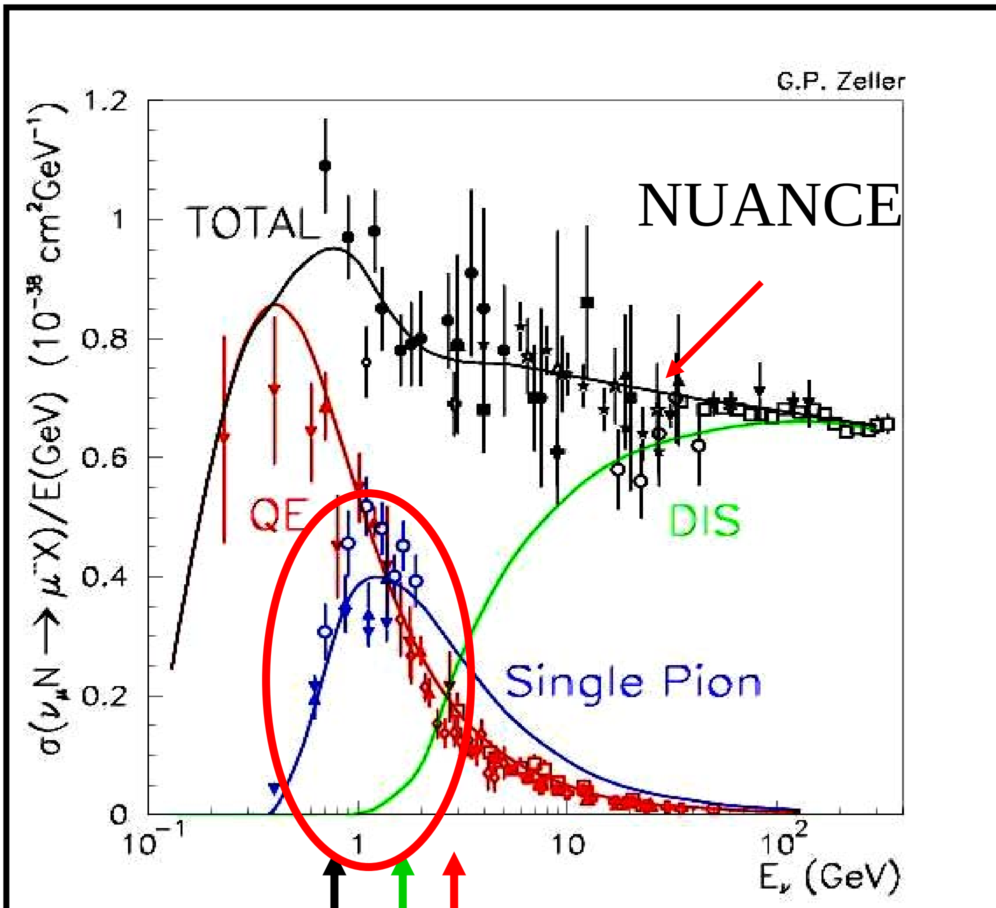
At 5 GeV, uncertainty of ~15% --> ~ 4%



In far/near ratio, hadron uncertainty largely cancels

Only small errors remain at focusing peak

Interlude - the physics of 0.5-5 GeV Neutrino Interactions



MINOS, NuMI

K2K, NOvA

MiniBooNE, T2K

Super-K atmospheric ν

Complex physics modeled as a combination of low-multiplicity processes

Pions are produced via intermediate resonant states

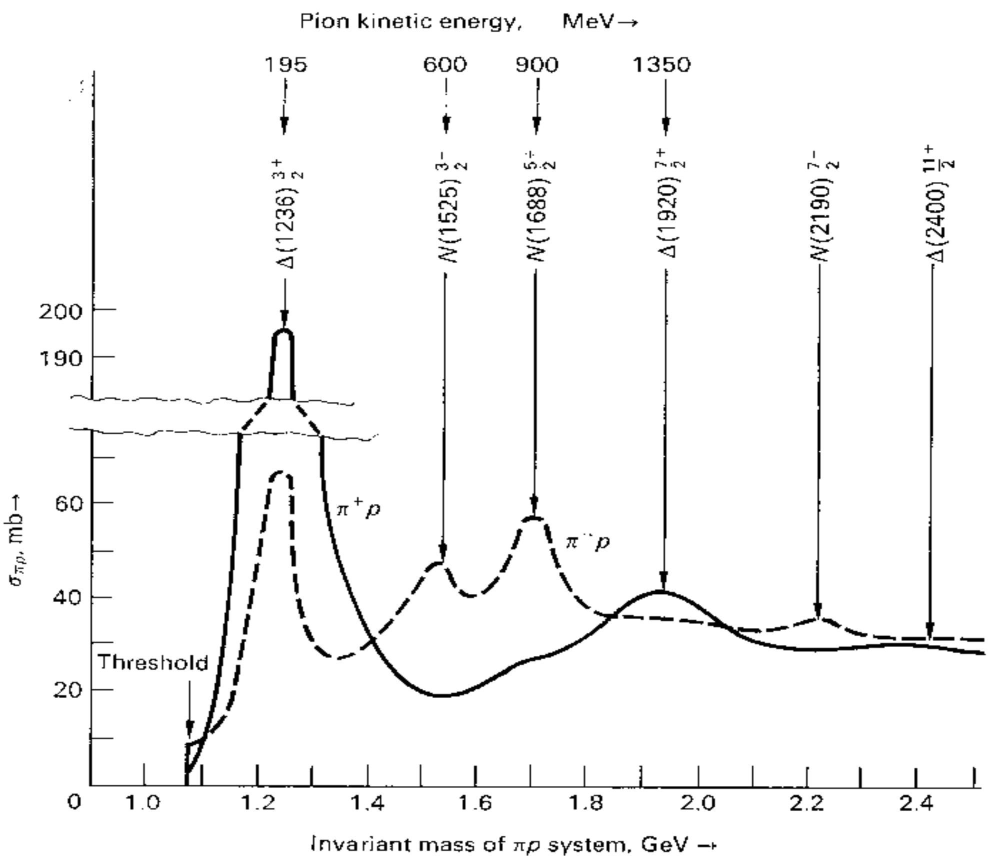
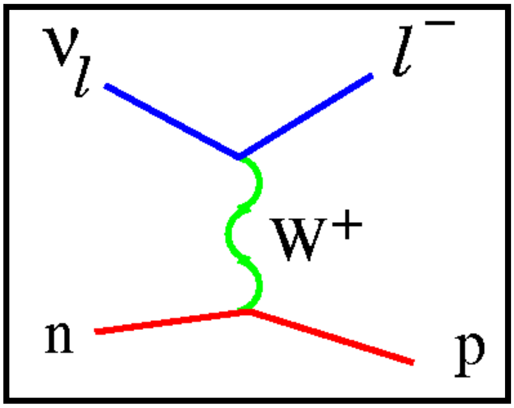


Fig. 4.6 Variation of total cross section for π^+ and π^- mesons on protons, with incident pion energy. The symbol Δ refers to resonances of $I = \frac{3}{2}$; N refers to $I = \frac{1}{2}$. The positions of only a few of the known states, together with their spin-parity assignments, are given.

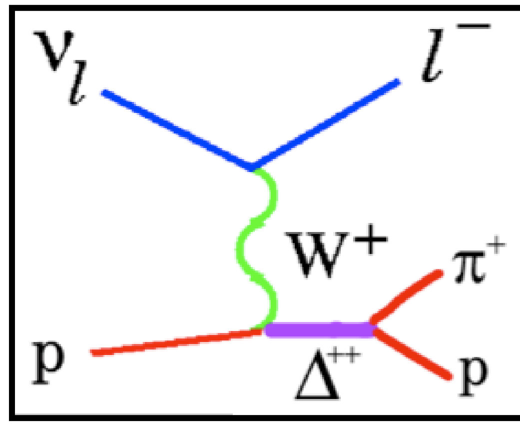
Resonances as observed in πn scattering experiments

(Figure from Perkins, Introduction to High Energy Physics

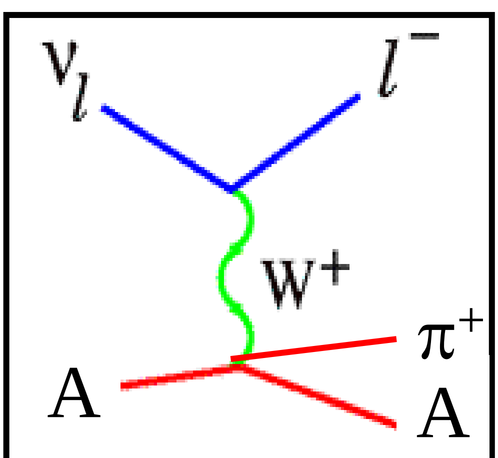
Different models have underlying physics in common



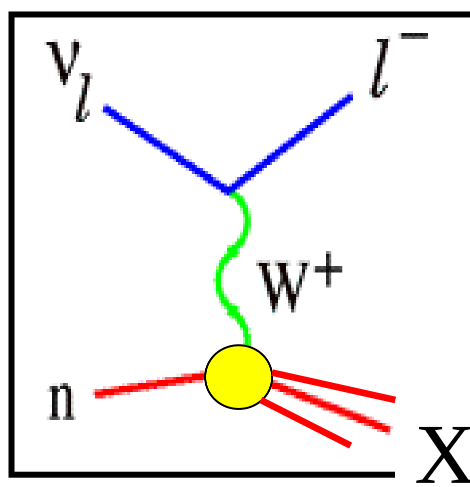
Quasi-elastic



Resonant π production



Coherent production



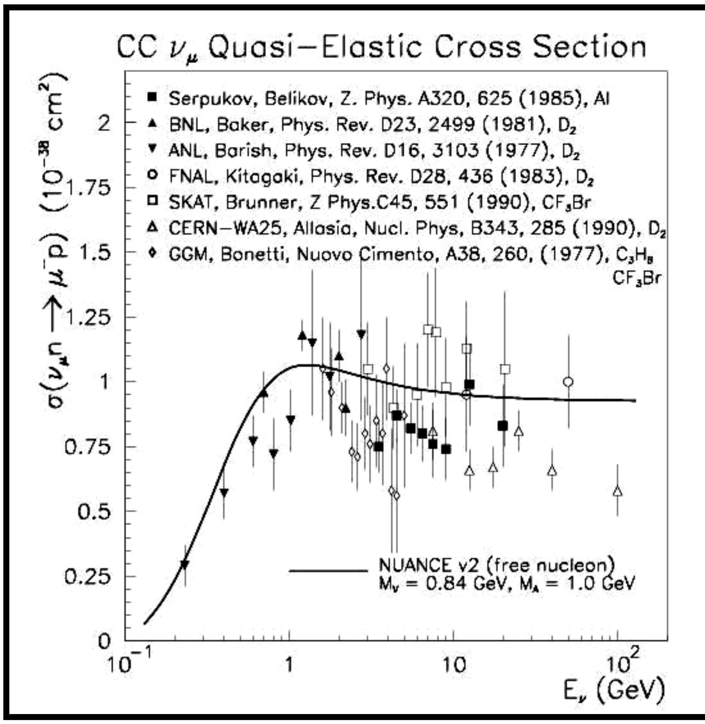
DIS

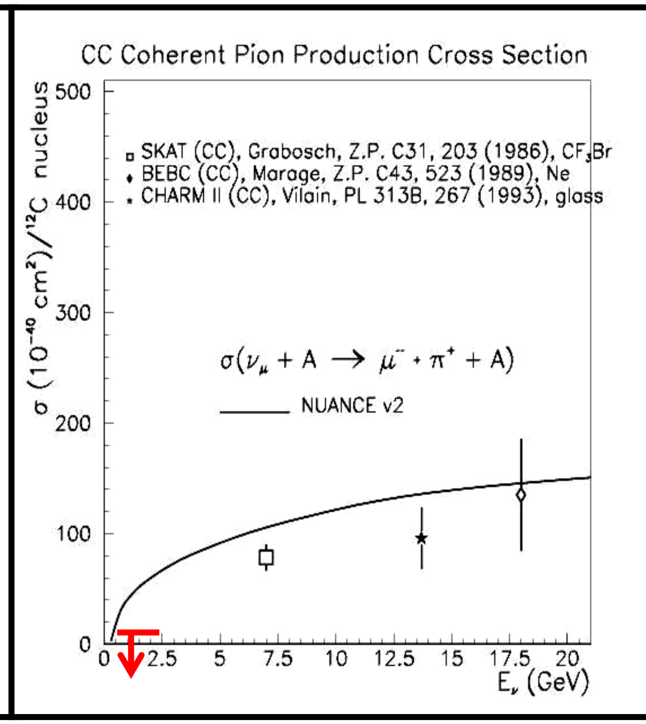
Different models combine channels differently.

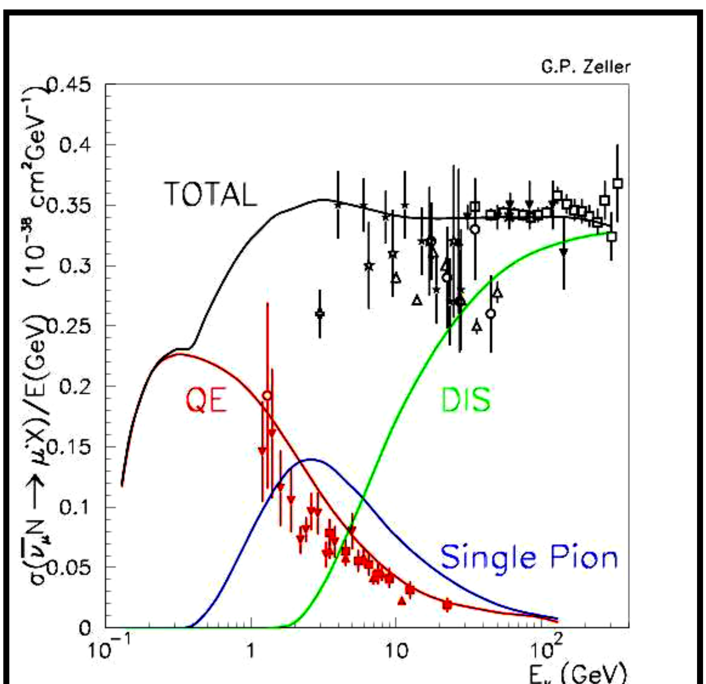
e.g. NUANCE - coherent addition of resonances

NEUGEN - incoherent addition

Existing data not strongly constraining





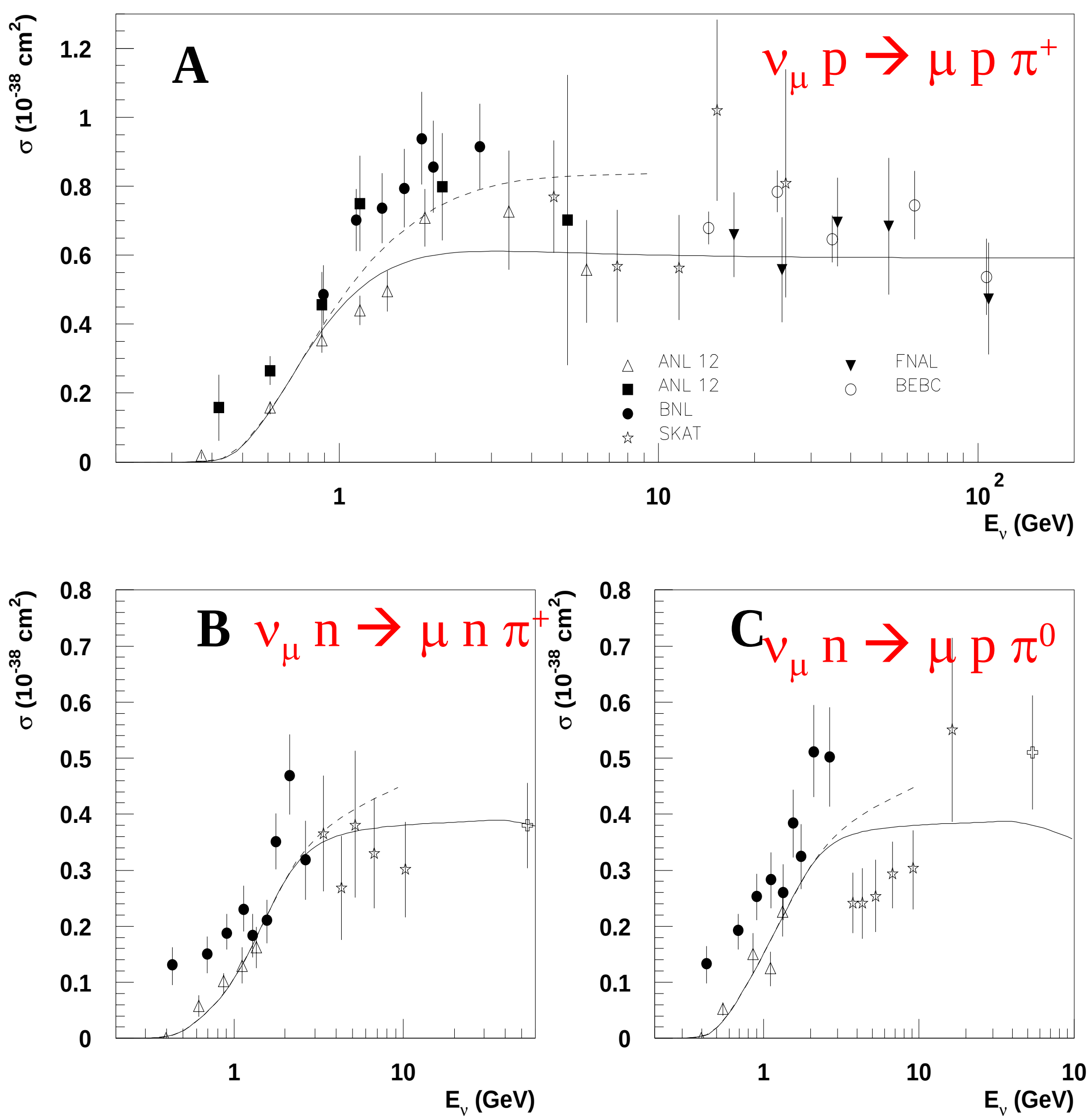


Coherent, ν–bar data basically nonexistent in region of interest.

Parameters in the models are tuned to exclusive channel cross sections.

$$\sigma_{tot} = \sigma_{QE} + \sum_i (\sigma^i_{res} + f_i \sigma^i_{DIS})$$

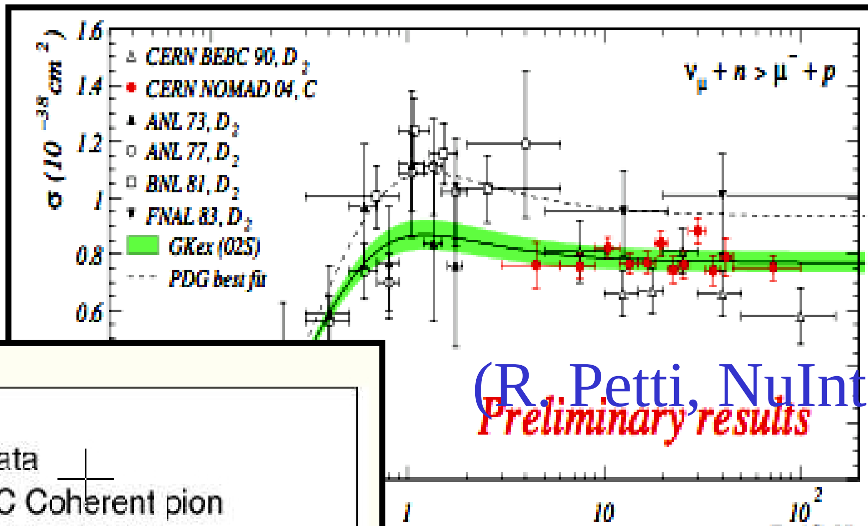
Charged Current Single Pion Production



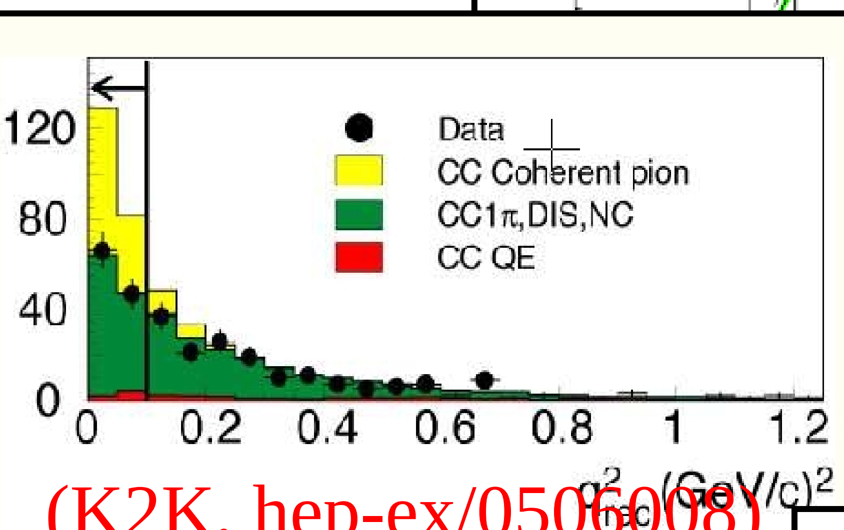
Examples from NEUGEN courtesy H. Gallagher

Worldwide effort to improve knowledge

•NOMAD, ^{12}C



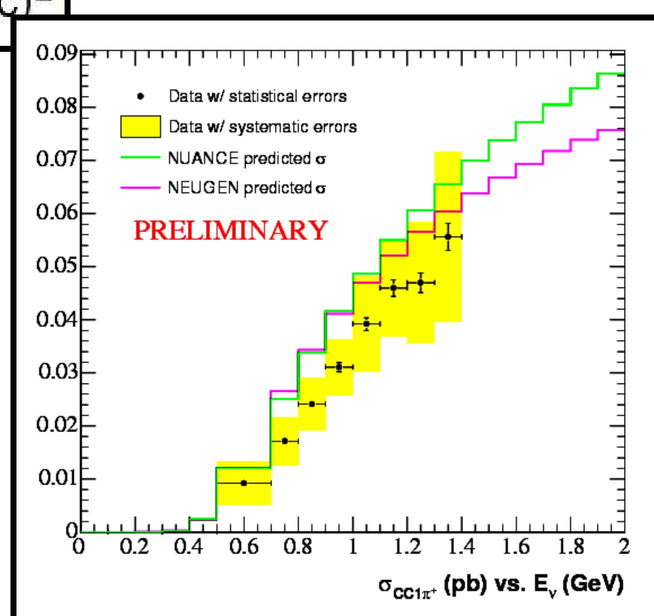
(R. Petti, NuInt05)



K2K, coherent $\pi+$

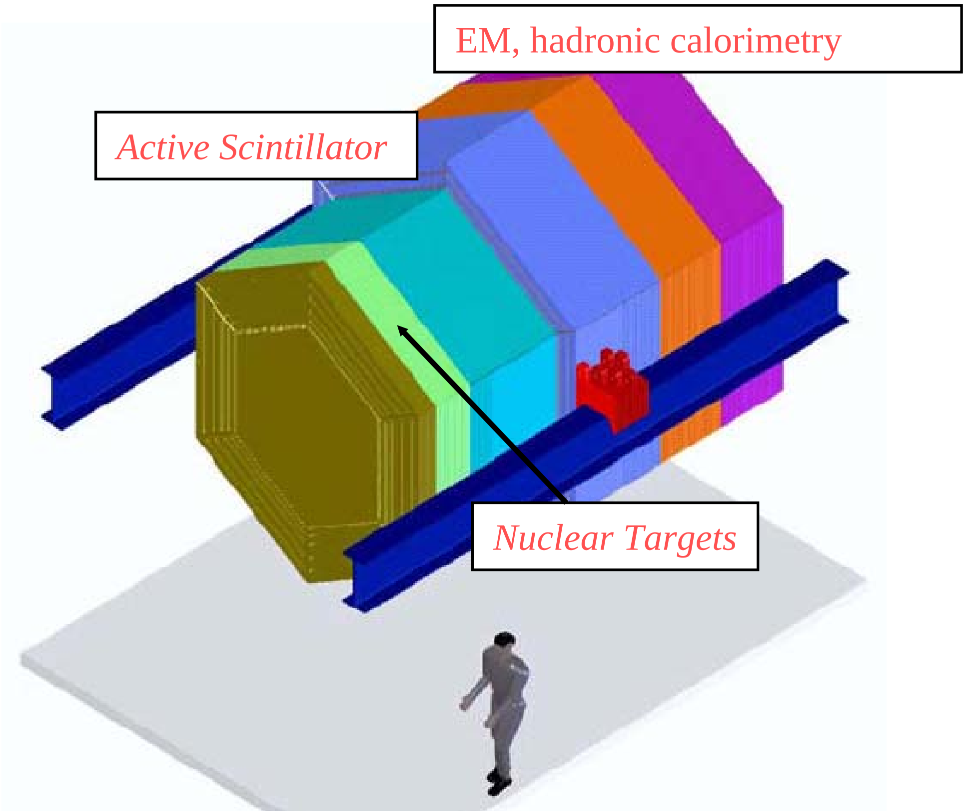
(K2K, hep-ex/0506008)

MiniBoone single π (Monroe,Wasco)



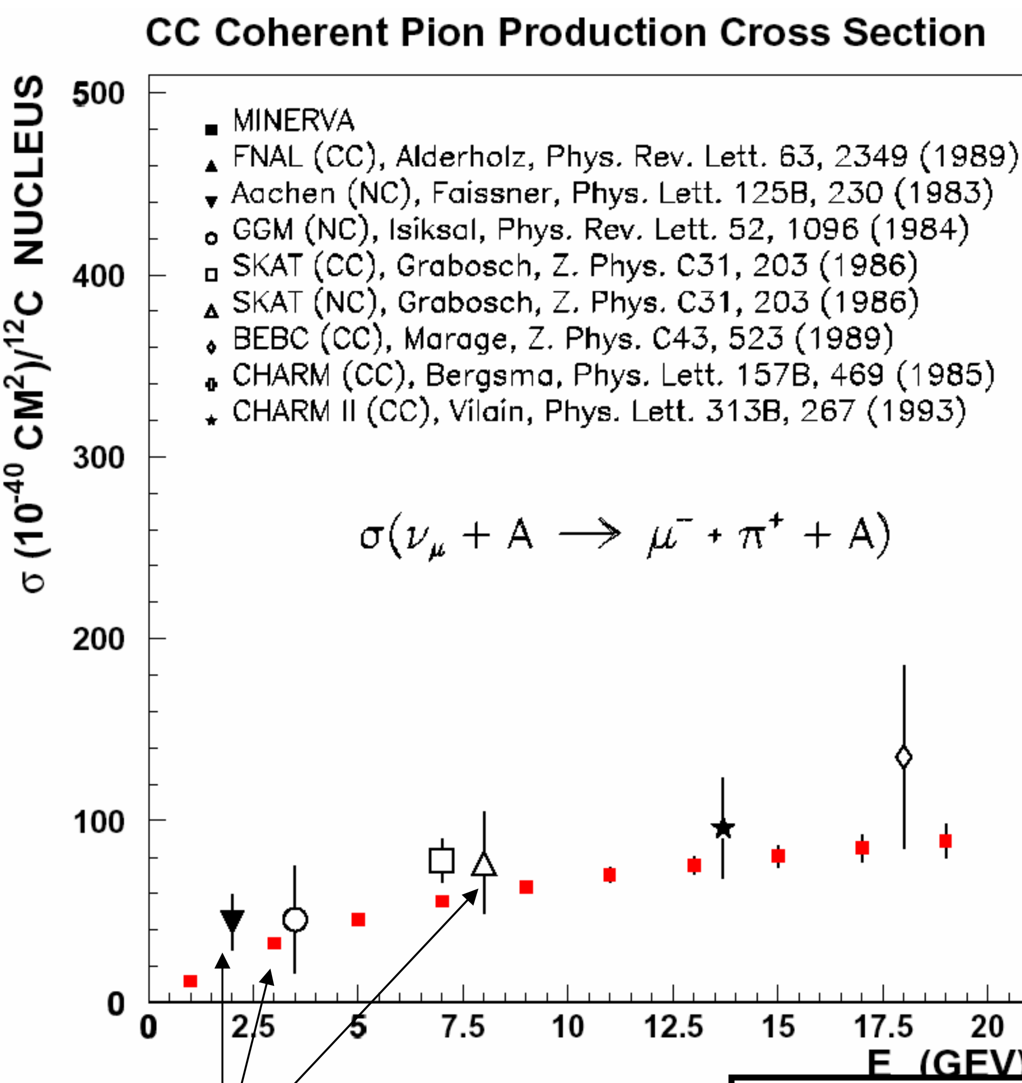
Plots courtesy G. Zeller, NOvE-06

MINERvA, a fine-grained neutrino scattering experiment

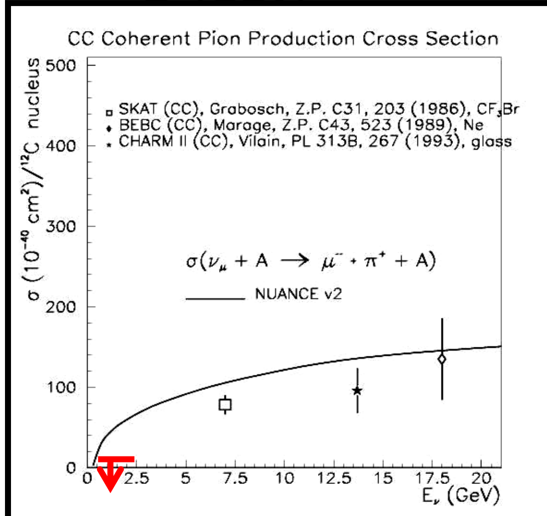


- Precision study of ν - nucleus scattering.
- Important for minimizing systematic errors of neutrino oscillation experiments
- To be located just upstream of MINOS Near Near Detector
- High-granularity, fully-active (~6T) scintillator strip based design.
- ~1 T of nuclear targets (C,Fe,Pb) form first detector section.

Example of MINERνA's Analysis Potential **Coherent Pion Production**



Some points are NC data rescaled to CC

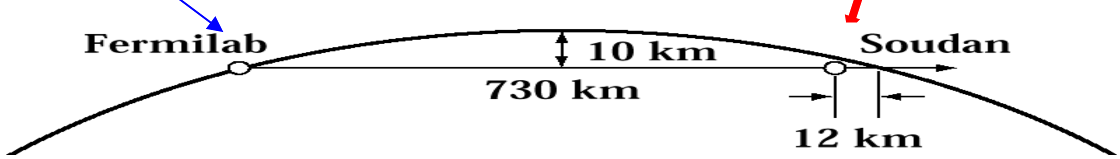


MINOS Long-Baseline Experiment

Fermilab to Soudan, Minnesota

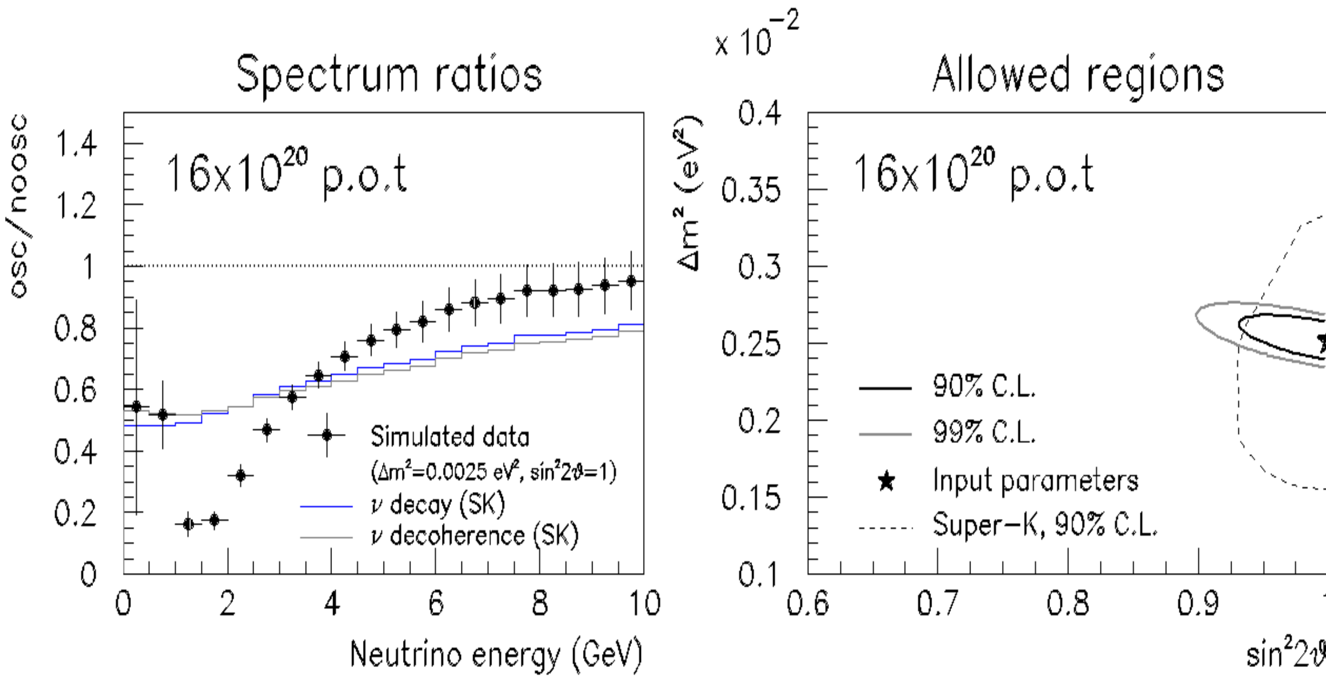
Far Detector: 5400 tons

Near Detector: 980 tons



km

Two-detector Disappearance Experiment



Study atmospheric scale

$\nu_\mu \rightarrow \nu_\tau$ Δm^2 *and* $\sin^2 2\theta_{23}$

Greatly improve existing measurement;

excellent test against alternative hypotheses

Sensitivity to ν_e appearance discussed later

The MINOS Far Detector

8m Octagonal Tracking Calorimeter

486 layers of 2.54cm magnetized Fe plates

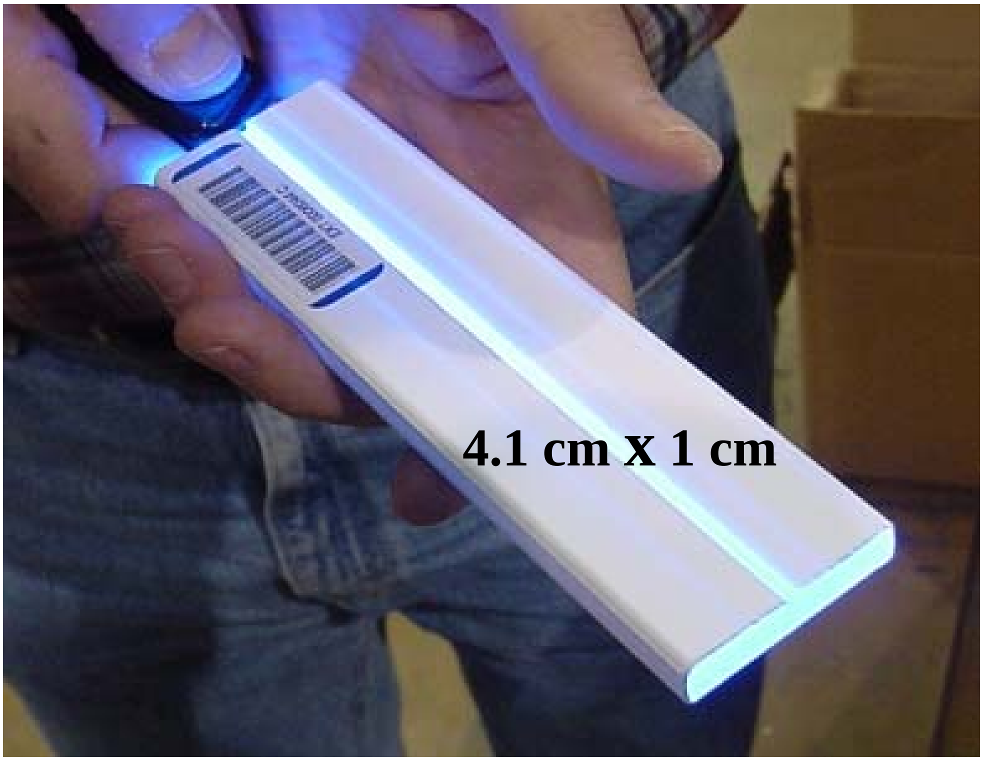
2 sections, each 15m long

4.1cm wide solid scintillator strips with WLS fiber readout (both ends).

Hamamatsu M16 multi-anode PMT readout

Veto shield against entering cosmic ray muons

Detector Technology



See talks by A. Pla-Dalmau, J. Grudzinski for more details.

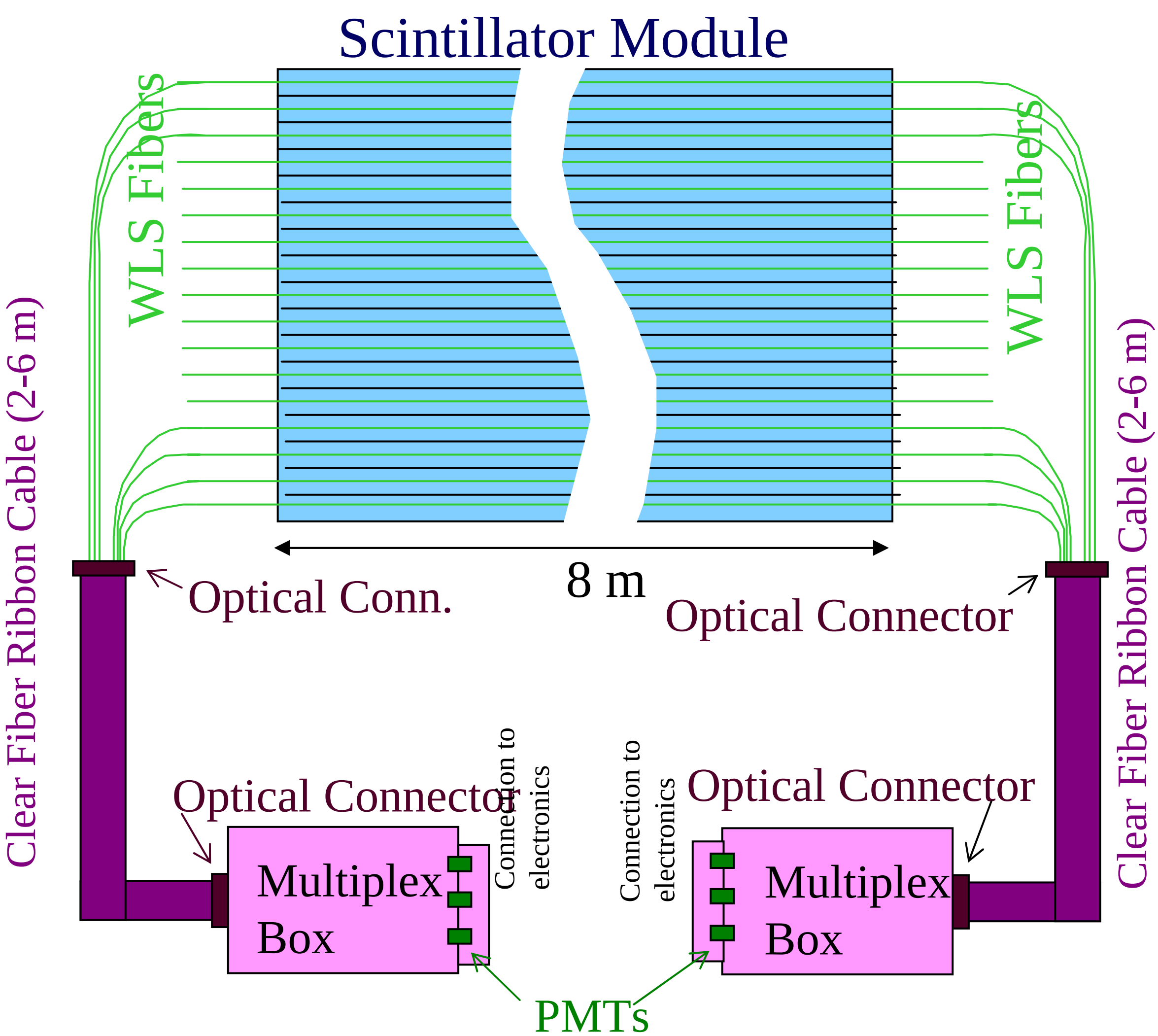
Scintillator strips are extruded polystyrene (Itasca Plastic)

1.2 mm Kuraray wavelength shifting fiber fits into groove

Groups of 20 or 28 strips are assembled into “modules”

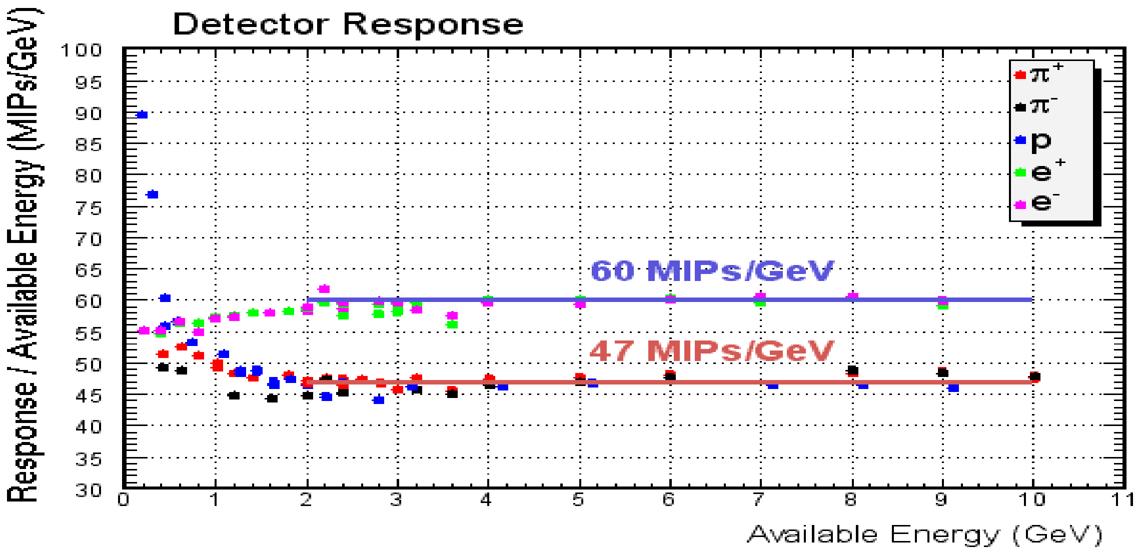
Both ends read out to increase light yield.

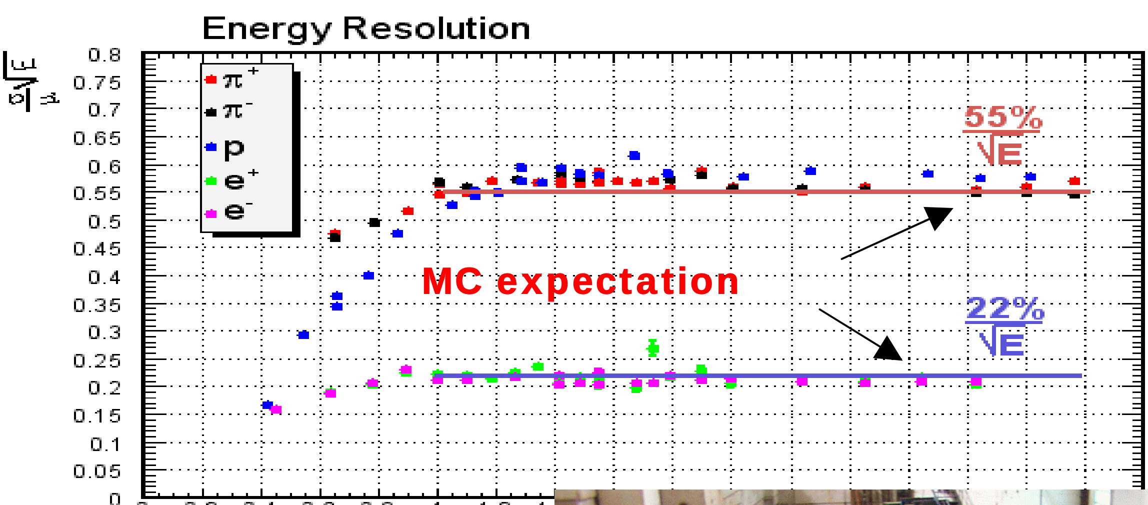
MINOS Detector Technology

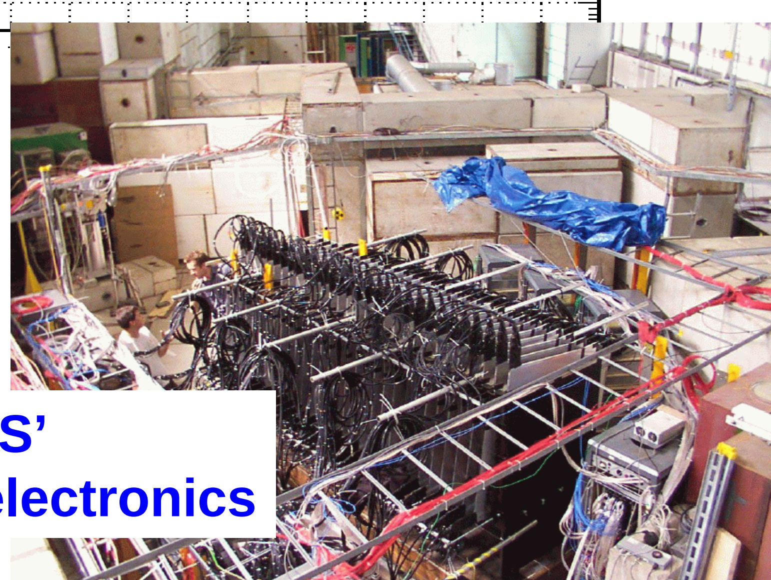


Objects not to scale

MINOS Calibration Detector at CERN

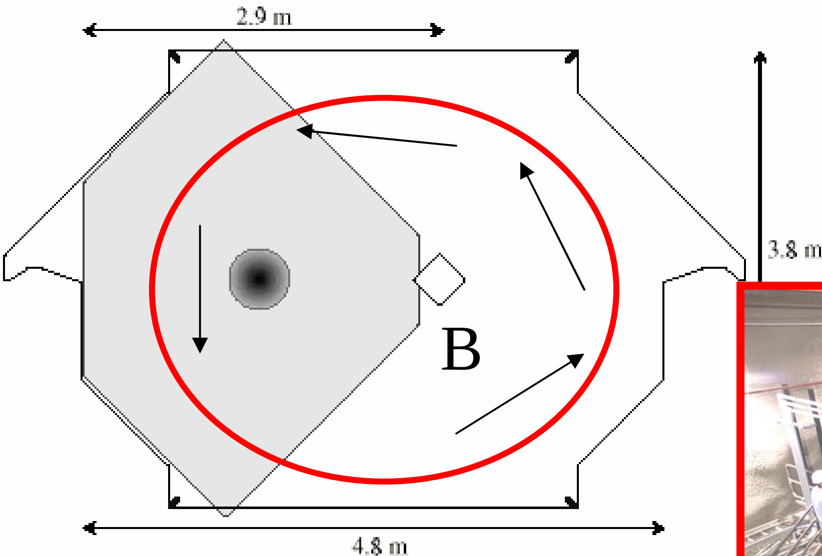






60-plane ‘micro - MINOS’
Also checked near/far electronics

MINOS Near Detector - slightly different



280 single steel plates, shorter modules

Calorimeter (1st 3/7 - logically Veto, Target, Hadron Absorber
is partially instrumented except for 1/5 of planes with full coverage

Muon Spectrometer section has only every 5th plane instrumented

Magnet coil provides <B> ~ 1.3 T

Near electronics optimized for high occupancy (~20) during 10 μs spill